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Guidelines for Design, Construction, and Evaluation of Airport Pavement Drainage

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Final Report

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16. Abstract

This report provides comprehensive guidelines for the design, construction, and evaluation of airport pavement drainage. Procedures for considering climatic effects on airport drainage are described. Brief summaries of several climatic models which can be used to generate temperature and moisture conditions in pavements are presented.

A review of the FAA design procedures for airport surface drainage is presented in order to maintain comprehensive coverage of all aspects of drainage in a single report. Pavement surface drainage is discussed in terms of pavement grooving and the use of porous friction courses.

Pavement subsurface drainage is discussed in detail. Methods for determining the sources and quantity of water which enter the pavement are provided. Procedures for designing subbase drainage layers, blankets and filter layers have been presented. Based on the sources and quantity of water which enters the pavement, methods for selecting and sizing the subdrainage collectors and outlets are discussed. Both the used conventional cirular pipe systems and prefabricated geocomposite subdrainage (PGS) systems are described.

The types of equipment and procedures for installation of pavement subsurface drainage are presented. The steps necessary for maintaining pavement subsurface drainage systems are discussed. Some of the methods for evaluating how well a subsurface drainage system is functioning are presented for information. The materials presented in chapters 1 through 7 fulfill the objectives stated for this report.

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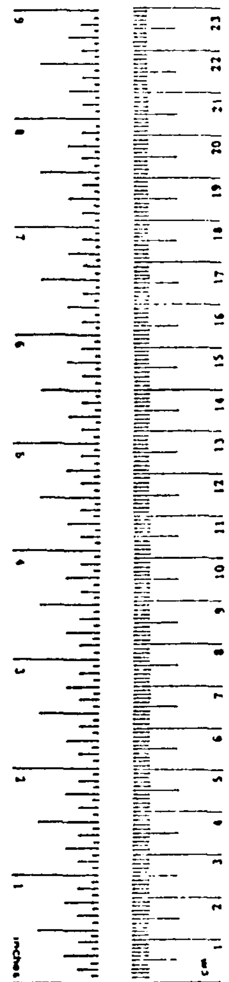
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

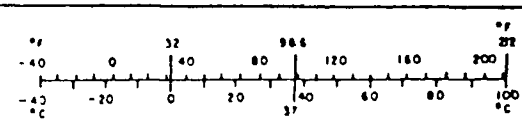
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13 10 286.



Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This Final Report on "Guidelines for Design, Construction, and Evaluation of Airport Pavement Drainage" was prepared for the U.S. Department of Transportation, Federal Aviation Administration with the direct supervision of the U.S. Army Corps of Engineers Construction Engineering Research Laboratory, Champaign, Illinois 61821, under contract Numbers DACA 88-85-M-0271, DACA 88-85-M-0786, DACW 88-85-D-0004-11 and DACW 88-85-D-0004-12 by the Department of Civil Engineering, University of Illinois, Urbana-Champaign, Illinois. Dr. Mohamed Shahin was the project coordinator for the U.S. Army Corps of Engineers.

This report completes all obligations specified in the contractual agreement with the U.S. Army Corps of Engineers Construction Engineering Research Laboratory.

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Chapter 1

INTRODUCTION

1.1 General

Surface and subsurface drainage are important considerations in the design of airport pavement systems. They are also important considerations in the repair, resurfacing, and reconstruction of existing airport pavement systems. Water is a major variable in most problems associated with pavement performance and it is responsible directly or indirectly for many of the distresses found in airport pavement systems.

Numerous reports which relate to the subject of airport pavement drainage have been summarized in the FAA Synthesis Report entitled "Airport Pavement Drainage" (1). Based on the Synthesis Report it has been become evident that there is a need to incorporate existing and new drainage concepts into a set of guidelines which could be used for surface and subsurface drainage of airport pavement systems.

There have been a considerable number of advances in subdrainage design, materials, construction, and evaluation over the last few years that have occurred mainly in the highway pavement areas. For this reason the major emphasis of this report will be placed on airport pavement subsurface drainage concepts.

1.2 Objectives

The main objective of this report is to present guidelines which can be used for the design, construction, and evaluation of airport pavement drainage systems. The specific objectives of this report are as follows:

1. Provide procedures for climatic considerations in airport drainage.
2. Review the general procedures used to determine the surface drainage requirements for airports.
3. Describe methods for improving pavement surface drainage.
4. Determine the sources and quantity of water that must be considered in pavement subsurface drainage.
5. Discuss different types of subsurface drainage which can be used in airport pavements.
6. Provide guidelines for the design of subsurface drainage systems for airport pavements.
7. Discuss types of equipment, installation procedures, and approximate costs for pavement subsurface drainage systems.
8. Describe procedures for evaluating and maintaining subsurface drainage systems in airport pavements.

Chapter 2

CLIMATIC CONSIDERATIONS IN AIRPORT PAVEMENT DRAINAGE

2.1 General

The first step in the design of airport pavement drainage is that of evaluating the climate for the location. Dempsey (1) has summarized the various climatic parameters important to airport drainage in a U.S. Army Engineer Waterways Experiment Station report entitled "Climatic Effects on Airport Pavement Systems; State of the Art." This report also provide pre-1976 methodology for incorporating climatic parameters into pavement design.

The most comprehensive procedure now available for evaluating the influence of water in pavement systems is described in Volumes 1 and 2 of the FHWA Reports entitled "A Pavement Moisture Accelerated Distress (MAD) Identification System (2,3). Volume 1 of the MAD Reports describes the development of the procedures for classifying the level of moisture impact on a pavement and Volume 2 is a users manual which provides the engineer with a rational method for determining the level of impact certain climatic zones and drainage conditions will have on pavement performance. Volume 2 of the MAD Reports also provides examples of the types of water related distresses in pavements and examples of the severity levels for these distresses.

In recent years several excellent models have been developed which provide methods for incorporating climatic parameter influence into pavement systems. These models include the Climatic-Materials-Structural (CMS) model developed at the University of Illinois, the CRREL FROST model from the U. S. Army Cold Regions Research and Engineering Laboratory, and the TTI Drainage model from the Texas Transportation Institute at Texas A&M University (4,5,6,7,8,9).

The CMS, CRREL FROST, and TTI Drainage models were recently combined into a single integrated model of the climatic effects on pavements. The Final Report describing the development and use of the Integrated Model entitled "An Integrated Model of the Climatic Effects on Pavements" was submitted to FHWA in February 1990 (10).

2.2 Climatic Considerations

Figure 2.1 shows the extrinsic parameters influencing temperature and moisture effects in pavement systems. In general the climatic factors which will have major influence on pavement drainage will be temperature, precipitation, location, and type of cover.

Cedergren et. al. (11) have indicated that subsurface drainage may not be needed in pavement systems where the average annual precipitation is less than 10 in., when the lateral drainage transmissibility of the base layer is 100 times greater than the infiltration rate, or when the combined lateral and vertical transmissibility of the base and subgrade exceed the vertical infiltration.

The moisture accelerated distress (MAD) system is a ranking procedure designed to separate pavements based on their potential to exhibit drainage problems (3). The first step in using the MAD system is to determine the climatic zone for the airport pavement being evaluated. Figure 2.2 shows the nine climatic zones which have been developed for the United States (2). These climatic zones are based on the Thornthwaite potential evapotranspiration and moisture index and temperature influence as shown in Table 2.1.

In general the moisture regions fall into the following categories:

Region I - Area which has a high potential for moisture present in the entire pavement structure during the entire year.

Region II - Area which displays a seasonal variability in the presence of moisture in the pavement structure.

Region III -An area in which there is very little moisture present in the pavement structure during the year.

The temperature regions are divided into the following:

Region A - This area has severe winters with a high potential for frost penetration to appreciable depths into the pavement subgrade.

Region B - Freeze-thaw cycles in the pavement surface and base course will be dominant in this area; however, severe winters may produce frozen subgrades with moderate frost penetration.

Region C - This area does not have a low temperature pavement problem, but high temperature pavement stability should be evaluated.

By following the procedures in Volume 2 of the FHWA MAD Report the drainability relationship for a granular subbase is determined from Figure 2.3 and for the subgrade from Table 2.2 (3). Depending on the drainage time shown in Figure 2.3 granular subbase materials may be classified as acceptable (a), marginal (m), or unacceptable (u). Subgrade drainage properties are based on AASHTO classification and topography as shown in Table 2.2. Subgrade soils are classified as poorly drained (i), moderately drained (j), or well drained (k). The findings from Figure 2.3 and Table 2.2 are combined with the moisture and temperature regions in Figure 2.2 to provide a ranking and MAD Index value as shown in Table 2.3 (3). As indicated in Table 2.3, the evaluation using the MAD procedure provides guidance in determining the potential level of damage that can occur in a pavement system as a result of climatic parameters and pavement internal drainage conditions. It can be easily seen from Table 2.3 that a pavement in a severe climatic zone such as Region 1-A placed on a granular base course which does not drain freely (value of u) and a subgrade classified as an AASHTO A-7-6 (value of i) would be given a combined rating of IAui which would indicate a high potential for moisture related distress.

The procedures outlined in the FHWA MAD system provide a realistic approach to the determination of drainage needs in relation to climate and pavement conditions.

2.3 Climatic-Materials-Structural (CMS) Program

2.3.1 General

The Climatic-Materials-Structural (CMS) program has been described in detail by Dempsey, Herlache, and Patel (4,5). Figure 2.4 shows how the climatic models (heat-transfer and moisture models) incorporated into the CMS program take climatic and material data as inputs and calculate temperature and moisture profiles as they vary with time in a pavement system. This information is used in the material models to calculate asphalt concrete, base course, subbase, and subgrade stiffness characteristics. The output can then be combined with load data and input into selected structural analysis models to generate data for analyzing flexible pavement behavior. Although the CMS program is mainly coded for flexible pavement systems it can be adapted to rigid pavement systems with only minor coding changes.

2.3.2 Heat-Transfer Model

A heat-transfer model developed by Dempsey (12) is one of the major subprograms used in the CMS program. The heat transfer model utilizes a finite difference solution to the one-dimensional, Fourier heat-transfer equation for transient heat flow to compute pavement temperatures with time. An energy balance procedure is used to predict pavement temperatures based on climatic parameters. Figure 2.5 shows a typical finite difference pavement system used in the heat-transfer model for computing pavement temperature. The pavement system consists of a column of nodes that have a unit cross-sectional area. Figure 2.6 shows those climatic parameters which relate to the radiation heat transfer and convection heat transfer into or out of the pavement system. The climatic inputs for the radiation heat transfer and convective heat transfer are easily obtained from weather station records in terms of air temperature, wind velocity, and percentage of sunshine data.

The procedures for determining the pavement thermal properties and moisture properties are described in detail in reports by Dempsey, Herlache, and Patel (4,5) and Dempsey (12).

2.3.3 CMS Program Output

Table 2.4 shows a partial output from the CMS program using the ILLI-PAVE algorithm analysis for 27 days of climatic data (4,5). The pavement system consisted of 8 in. of asphalt concrete placed on 6 in. of A-2 subbase material and an A-6 subgrade. The strengths of the asphalt concrete and subgrade layers were obtained through use of the CMS program and the pavement deflection and deflection basin area determined from the ILLI-PAVE algorithms.

Although the data in Table 2.4 were determined for a flexible pavement system, the same procedure can be followed for rigid pavement applications. The output data can also be used in conducting durability studies on pavement materials used in the various pavement layers.

2.4 Integrated Climatic Model

2.4.1 General

The Integrated Climatic Model represents the most comprehensive and detailed model for evaluating climatic effects on pavement systems at this time (10). This model shown in Figure 2.7 is composed of four major components. These components include a Precipitation Model, the TTI Infiltration and Drainage Model, the University of Illinois CMS Model, and the CRREL FROST Model (10). The Integrated Model is developed to run on 286 and 386 models of microcomputers. The program is written in Fortran 77 language. The Integrated Model is highly user friendly and can be easily used by following the guidelines in the FHWA Final Report (10).

2.4.2 Capabilities of the Integrated Model

The Integrated Model is one-dimensional coupled heat and moisture flow program which is intended for use with pavements, which has the capability of generating internally realistic patterns of rainfall, solar radiation, cloud cover, wind speed, and air temperature to simulate the upper boundary conditions, and which has a variety of options for specifying the moisture and temperature, or the flux of these at the lower boundary and at the interface between the subgrade and the base course. It has the unique ability to consider the lateral and vertical drainage of the base course, which is a two-dimensional problem, in determining the amount of water that enters the subgrade by infiltration through the pavement surface and base. The program steps forward in time with time steps that cover 0.125 hours at a time, and boundary conditions must be generated throughout each day at that interval for a full year. The severity of the weather patterns, both of rainfall and temperature, may be controlled by the user by setting the desired confidence level, with the higher levels providing the colder winters, the hotter summers, and the greater amounts of rainfall.

The program estimates the depth of the frost zone, the amount of ice that has formed in each vertical increment, the negative porewater pressure in the unfrozen water at temperatures below freezing, the mean and maximum frost heave that may be expected each day, and the elastic moduli of the pavement layers at each nodal point as they are affected by the computed moisture and temperature.

2.4.3 Input Data

A data input program has been provided to make the task of specifying input data as simple and as user friendly as possible. A complete set of default input data is provided both to give the user guidance on appropriate values and to be used in the problem if the user chooses to select them. Both the data input program and the Integrated Models program run on a microcomputer. The data input program creates the necessary data input files, the names of which displayed on the screen at the conclusion of the input process.

Weather data files for 15 cities representing each of the 9 climatic regions, Figure 2.2, in the United States are included in the data provided with the program, and in most cases these data represent summaries of 30 years

of weather at each location. The user may elect to use the data for one of the 15 listed cities, Table 2.5, or if the site being investigated is not one of the cities listed, the user may select the climatic region in which the site is located. In the latter case, the program will take the average of the data from the two cities in that region. Three of the regions are so small that they are represented by only one city. The user may input weather data which have been collected at any other specific site, if desired. The data required are the same as that being recorded in the Strategic Highway Research Program Long Term Pavement Performance project.

2.4.4 Output Data

The user may select the amount of output desired, and an enormous amount can be generated if that is wanted. Normally, only summary data are desired and that, too, may be selected at the user's option. The data output can include daily porewater pressures and temperatures at selected depths and at one to three times during each day. Output also may include the frost and thaw depth, maximum and mean frost heave each day, as well as the moduli of the pavement layers at each nodal point each day if desired. Figure 2.7 shows the various outputs of the Integrated Climatic Model which include such parameters as temperature profile, suction profile, frost penetration, thaw depth, drainage, and material property changes as a function of time. The output data is presented in tabular form or, in some cases, it can be graphed by the model graphics program.

2.4.5 Program Uses

The Integrated Climatic Model program is intended to be used to provide data for design support. The design of pavements should be based upon realistic expectations of how the materials in each layer will respond to climatic influences of a desired level of severity specified by the user. A default confidence level of 95 percent has been set within the program to subject the pavement to air temperatures and rainfall patterns that are more severe than 95 percent of the data that have been selected at each site.

The model has been found to be very sensitive and realistic in its ability to match measured field data within reasonable expectations. Some experience with the model in matching measured data is an invaluable aid to mastering its use. The information contained in Chapters 7 and 8 of the FHWA Final Report will provide valuable assistance in gaining this experience (10).

2.4.6 Limitations of the Integrated Model

It is realistic to recognize not only the capabilities but also the limitations of the Integrated Model so as not to require more from it than it can provide or to have the frustrating experience of having overly optimistic expectations remain unfulfilled.

The program is one-dimensional despite the use of the TTI Infiltration and Drainage Model to simulate the effects of lateral as well as vertical drainage. The actual pavement infiltration and drainage patterns are at least two-dimensional, especially near the edge of the pavement.

The program does not presently have the capability of predicting vertical movements in expansive and collapsing soils due to changes of moisture and negative porewater pressure, although the changes required to provide it with this ability are fairly simple.

Although the Integrated Model can be used as a research tool, its primary purpose is intended for design studies. Because of the importance of weather data in pavement performance the required weather data used in the model are very easily obtained from the U.S. Weather Bureau. The emphasis on weather data was simplicity and ease of use. For this reason the objective was not to duplicate nature exactly, but to simulate realistic weather patterns at a user-selected level of severity.

2.5 Summary

This chapter provides several procedures for evaluating the influence of climate on the water content in pavements. The MAD system defines the potential for water damage to pavements based upon climatic region, base course drainage rating, and subgrade type.

The CMS program provides a detailed procedure for determining pavement temperatures and moisture contents based on climatic input data. The pavement material properties can be generated as a function of temperature and moisture changes for utilization in pavement thickness design and construction evaluation.

The Integrated Model is the most comprehensive computer available at this time. It can generate transient water content profiles in a pavement system based on climatic data input. This model also provides data on pavement profile temperature, frost heave, and layer strength.

REFERENCES

1. Dempsey, B. J., "Climatic Effects on Airport Pavement Systems; State of The Art," Report S-76-12, U. S. Army Corps of Engineers and Federal Aviation Administration, Washington, D. C., 1976.

2. Carpenter, S. H., Darter, M. I., and Dempsey, B. J., "A Pavement Moisture Accelerated Distress (MAD) Identification System, Vol. 1, Final Report No. FHWA/RD-81/079, Federal Highway Administration, Washington, D.C., 1981.

3. Carpenter, S. H., Darter, M. I., and Dempsey, B. J., "A Pavement Moisture Accelerated Distress (MAD) Identification System, Vol. 2," Final Report No. FHWA/RD-81/080, Federal Highway Administration, Washington, D., 1981.

4. Dempsey, B. J., Herlache, W. A., and Patel, A. J., "The Climatic-Materials-Structural Pavement Analysis Program," Final Report FHWA/RD-84/115, Vol. 3, Federal Highway Administration, Washington, D. C., 1985.

5. Dempsey, B. J., Herlache, W. A., and Patel, A. J., "Climatic-Materials-Structural Pavement Analysis Program," Transportation Research Record No. 1062, Transportation Research Board, Washington, D. C., 1986.

6. Guymon, G. L., Berg, R. L., Johnson, T. C., and Hromadka, T. V., "Mathematical Model of Frost Heave and Thaw Settlement in Pavements," CRREL Report, U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, N. H., 1986.

7. Berg, R. L., Guymon, G. L., and Johnson, T. C., "Mathematical Model to Correlate Frost Heave of Pavements with Laboratory Predictions, Report No. FAA-RD-79-109, U. S. Department of Transportation, Federal Aviation Administration, Washington, D. C., 1980.

8. Liu, S. J. and Lytton, R. L., "Environmental Effects on Pavements-Drainage Manual," Final Report, FHWA/RD-84/116, Vol. 4, Federal Highway Administration, Washington, D. C., 1985.

9. Liu, S. J., Jeyapalan, J. K., and Lytton, R. L., "Characteristics of Base and Subgrade Drainage of Pavements," Transportation Research Record 945, Transportation Research Board, Washington, D. C., 1983.

10. Lytton, R. L., Pirfahl, D. E., Michalik, C. H., Liang, H. S., and Dempsey, B. J., "An Integrated Model of the Climatic Effects on Pavements," Final Report, FHWA RD-90-033, Federal Highway Administration, Washington, D. C., 1990.

11. "Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections," FHWA-RD-72-30, Federal Highway Administration, Washington, D. C., 1972.

12. Dempsey, B. J., "A Heat-Transfer Model for Evaluating Frost Action and Temperature Related Effects in Multilayered Pavement Systems," Thesis, Department of Civil Engineering, University of Illinois, Urbana, 1969.

Table 2.1 Description of Climatic Zones.

Moisture Region		Temperature Region A	Temperature Region B	Temperature Region C
Potential of Moisture Being Present in Pavement Structure During Typical Year		Severe Winters High Potential for Frost Penetration to Appreciable Depths Into Subgrade	Freeze-Thaw Cycles in Pavement Surface and Base Occasional Moderate Freezing of Subgrade	Low Temperature Not a Problem High Temperature Stability Should Be Considered
I	High	I-A	I-B	I-C
II	Moderate Seasonally Variable	II-A	II-B	II-C
III	Low	III-A	III-B	III-C

Table 2.2 Drainage Classification for Subgrade Soils (Ref. 3).

i = Poorly Drained Subgrade

j = Moderately Drained Subgrade

k = Well Drained Subgrade

AASHTO Class. \ Position in Topography.	Top of Hills	Sides of Hills	Depressions
A-1 A-3	k	k	k
A-2-4 A-2-5	k	k	j
A-2-6 A-2-7	k	k	j
A-4	k	j	j
A-5	j	j	i
A-6	j	i	i
A-7-5 A-7-6	i	i	i

A group index above 20 will alter the NDI rating, k → j , j → i.

A group index below 5 will alter the NDI rating, i → j , j → k .

MAD Index	Damage Potential	Combinations				
100	NEGLIGIBLE					
99						
98						
97						
96						
95						
94						
93						
92		III Cak				
91						
90						
89		III Cmk				
88						
87						
86						
85		III Caj	III Bak			
84	LOW					
83						
82		III Bmk				
81						
80						
79						
73		III Caj	III Cmj	III Baj	III Cuk	III Aak
77						
76						
75		III Amk				
74		II Cak				
73						
72						
71		III Cuk	III Bmj	III Aaj	III Buk	II Cmk
70		III Cmi	III Bai			
69	NORMAL					
68						
67		II Caj	II Bak			
66						
65						
64		III Buk	III Amj	III Auk	II Bmk	
63		III Cui	III Bmi	III Aai		
62						
61						
60		II Cmj	II Baj	II Cuk	II Auk	
59		II Cai				
58						
57		III Auk	II Amk			
56		III Bui	III Ami			
55						

MAD Index	Damage Potential	Combinations					
54	MODERATE	I Cak					
53		II Cmi	II Bai	II Cuk	II Bmj	II Auj	II Buk
52							
51		I Cmk					
50							
49		III Aui					
48							
47		I Caj	I Bak				
46		II Buk	II Amj	II Auk			
45		II Cui	II Bmi	II Aui			
44		I Bmk					
43							
42							
41							
40		I Cmj	I Bai	I Cuk	I Aak		
39		II Auk	I Cai				
38		II Bui	II Ami				
37		I Amk					
36							
35							
34	HIGH						
33		I Cuj	I Bmj	I Aaj	I Buk		
32		I Cmi	I Bai				
31		II Aui					
30							
29							
28							
27							
26		I Buj	I Amj	I Auk			
25		I Cui	I Bmi	I Aai			
24							
23							
22							
21							
20							
19		I Aui					
18		I Bui	I Ami				
17							
16							
15							
14	EXCESSIVE						
13							
12							
11		I Aui					
10							
9							
8							
7							
6							
5							
4							
3							
2							
1							
0							

Table 2.3 Ranking and MAD Index Based on Subbase and Subgrade Drainage and Geographical Location (Ref. 3).

Table 2.4 Partial Output from Combined CMS Program and ILLI-PAVE Algorithm Analysis (Ref. 4).

PAVEMENT SYSTEM

LAYER	TYPE	THICK.
1	IMPERM	4.00
2	IMPERM	4.00
3	A-2	6.00
4	A-6	130.00

DATE	AVG AC TEMP (C)	AVG AC E (KSI)	AVG SUBGRADE E (KSI)	DEFLECTION (MILS)	AREA (IN)
1	18.16	.1250E+04	.5636E+01	13.671	24.628
2	18.82	.1224E+04	.5636E+01	13.835	24.522
3	20.94	.1151E+04	.5636E+01	14.309	24.222
4	21.86	.1119E+04	.5636E+01	14.519	24.093
5	25.82	.9962E+03	.5636E+01	15.364	23.591
6	26.87	.9655E+03	.5636E+01	15.583	23.465
7	32.74	.8128E+03	.5636E+01	16.718	22.841
8	34.98	.7596E+03	.5636E+01	17.133	22.623
9	42.91	.6051E+03	.5632E+01	18.400	21.993
10	45.12	.5699E+03	.5632E+01	18.700	21.849
11	48.87	.5168E+03	.5623E+01	19.172	21.635
12	50.04	.4988E+03	.5623E+01	19.331	21.561
13	51.34	.4843E+03	.5595E+01	19.485	21.512
14	52.37	.4692E+03	.5595E+01	19.620	21.450
15	52.87	.4651E+03	.5518E+01	19.727	21.461
16	53.90	.4495E+03	.5518E+01	19.869	21.397
17	57.31	.4073E+03	.5441E+01	20.330	21.253
18	57.65	.4030E+03	.5441E+01	20.370	21.235
19	58.74	.3922E+03	.5364E+01	20.544	21.219
20	58.89	.3901E+03	.5364E+01	20.564	21.210
21	59.42	.3854E+03	.5286E+01	20.680	21.218
22	59.54	.3836E+03	.5286E+01	20.698	21.211
23	59.98	.3800E+03	.5209E+01	20.805	21.224
24	60.05	.3786E+03	.5209E+01	20.818	21.218
25	60.46	.3754E+03	.5132E+01	20.922	21.233
26	60.54	.3740E+03	.5132E+01	20.936	21.227
27	60.85	.3717E+03	.5055E+01	21.031	21.246

AVERAGE DEFLECTION OVER ANALYSIS PERIOD (MILS) 18.635

ASPHALT CONCRETE RADIAL STRAIN (IN/IN) .2021E-03

ALLOWABLE NUMBER OF 18K EQAL 3120475

Table 2.5 Representative Cities for the Nine Climatic Regions (Ref. 10).

Moisture Region	Temperature Region		
	A	B	C
I	New York, NY Chicago, IL	Washington, D.C. Cincinnati, OH	San Francisco, CA Atlanta, GA
II	Fargo, ND Lincoln, NE	Oklahoma City, OK	Dallas, TX
III	Reno, NV Billings, MT	Las Vegas, NV San Angelo, TX	San Antonio, TX

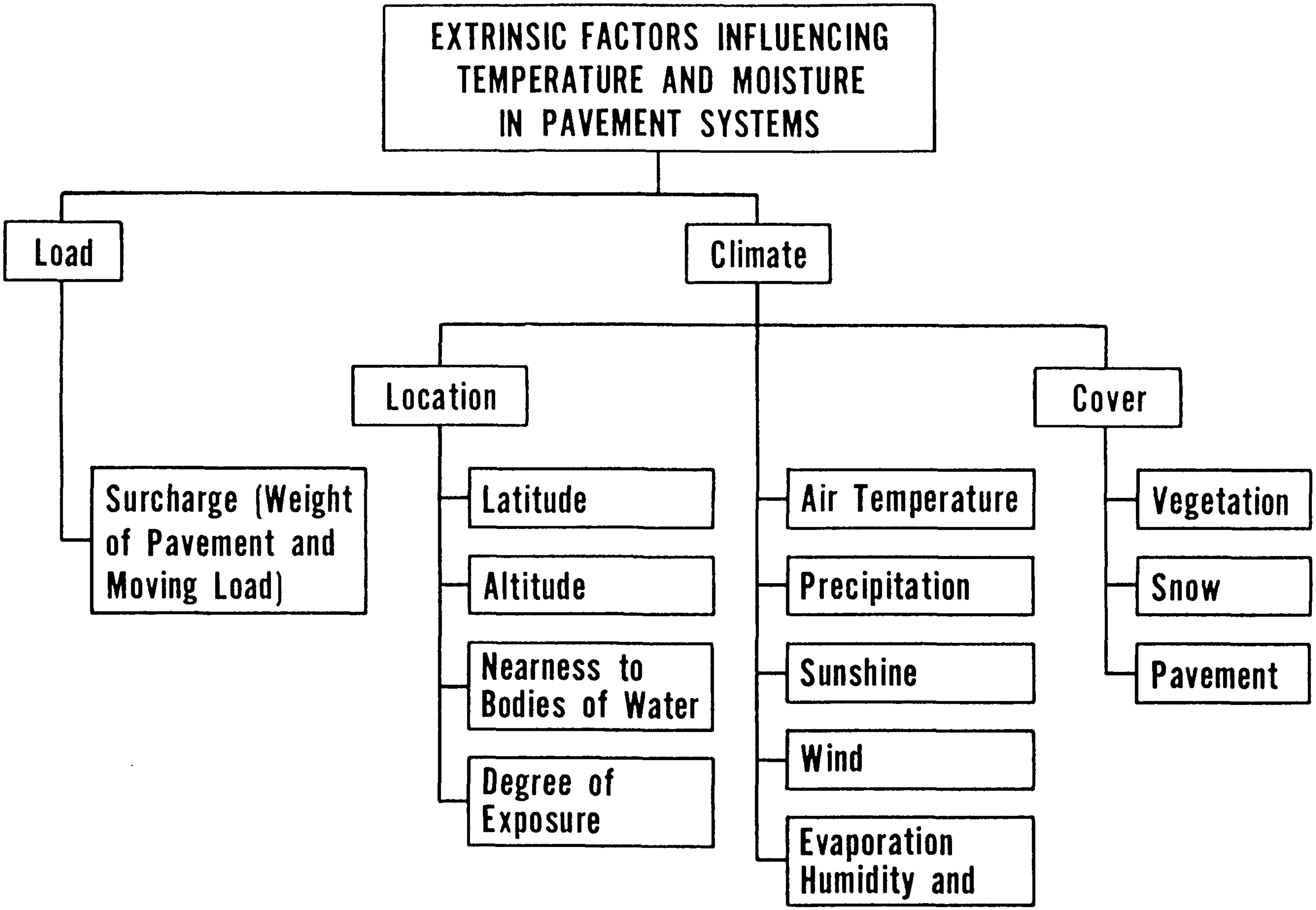


Figure 2.1 Extrinsic Factors Influencing Temperature and Moisture in Pavement Systems.

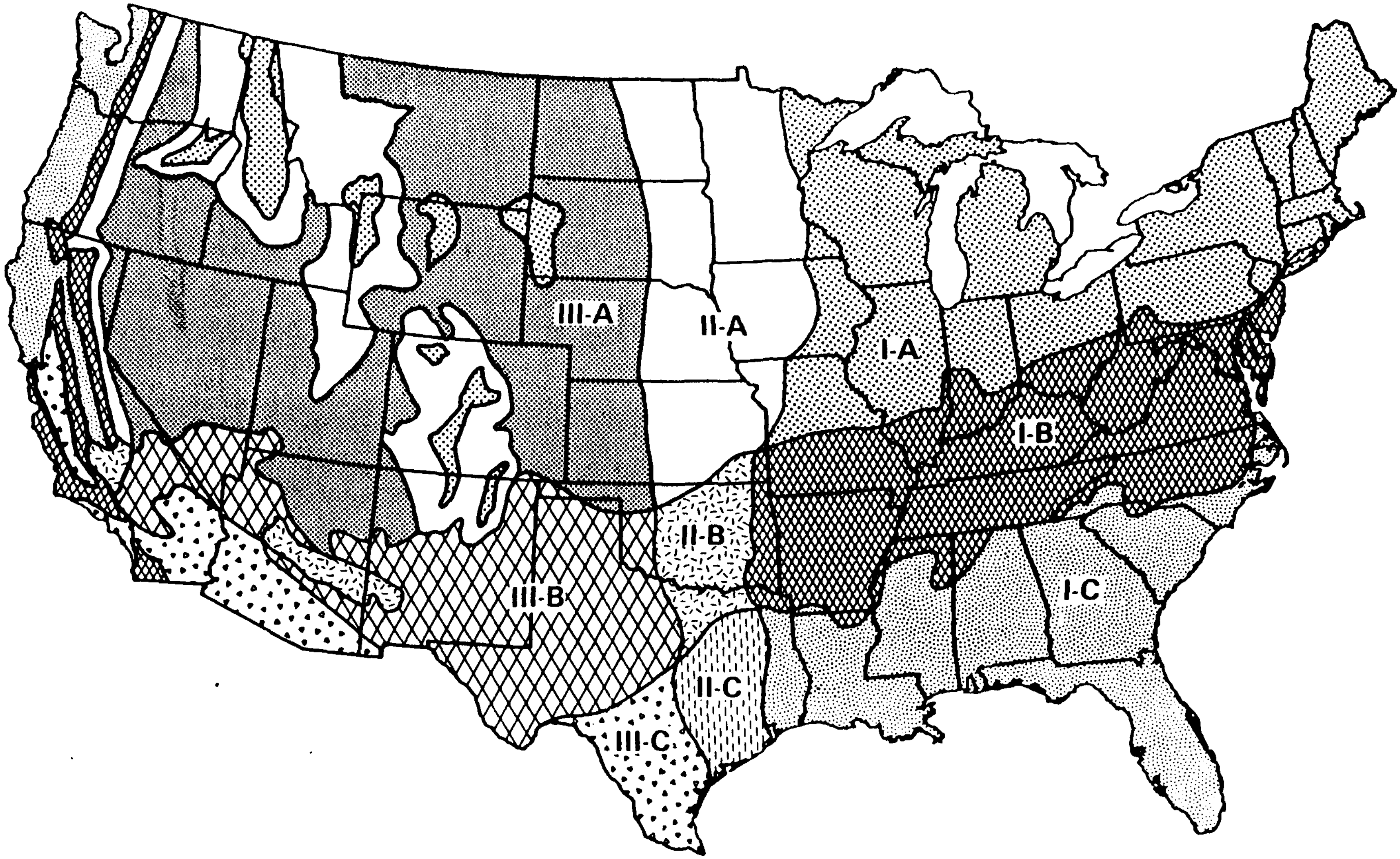


Figure 2.2 Nine Climatic Zones in the United States (Ref. 2).

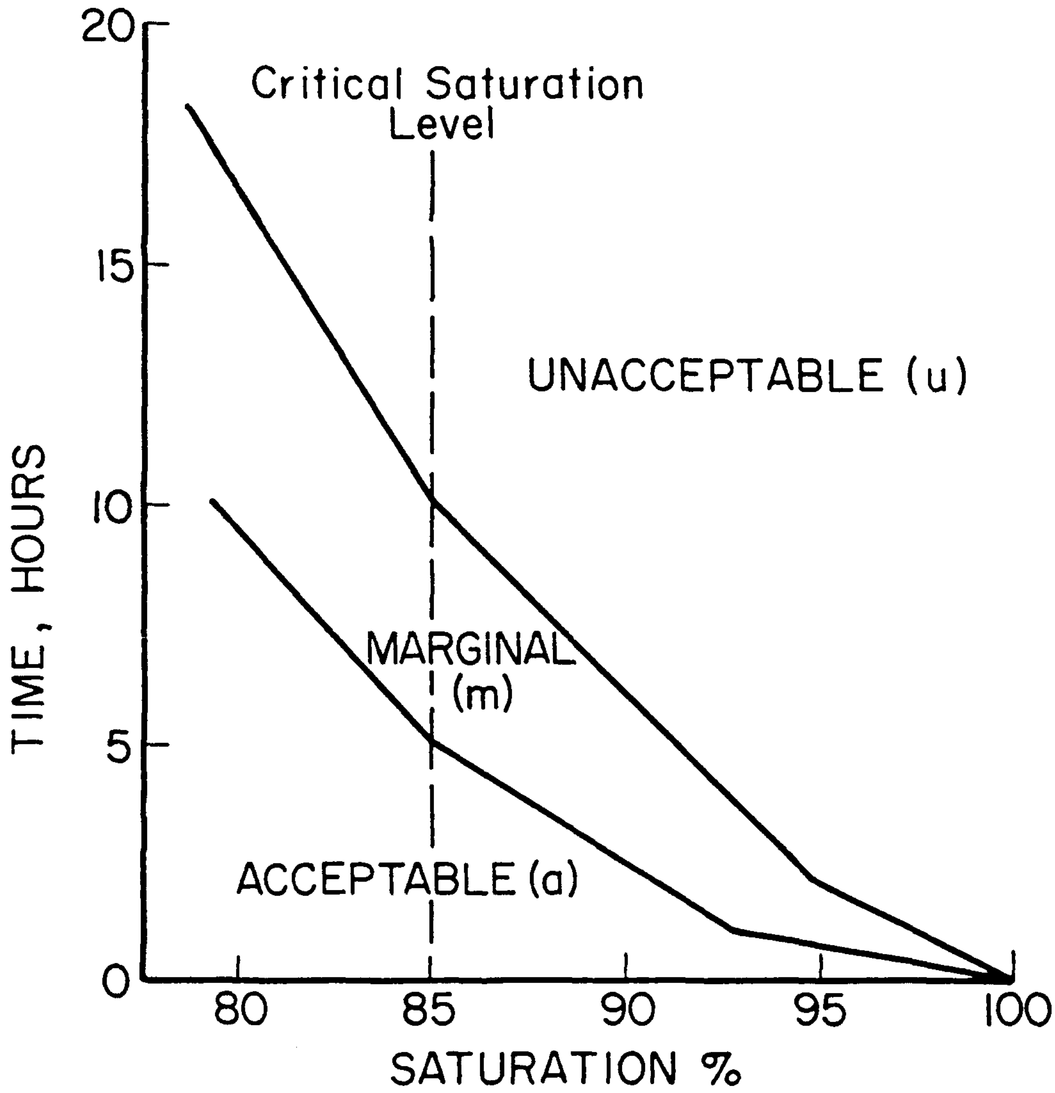


Figure 2.3 Drainability Relationships for Granular Subbase Material (Ref. 3).

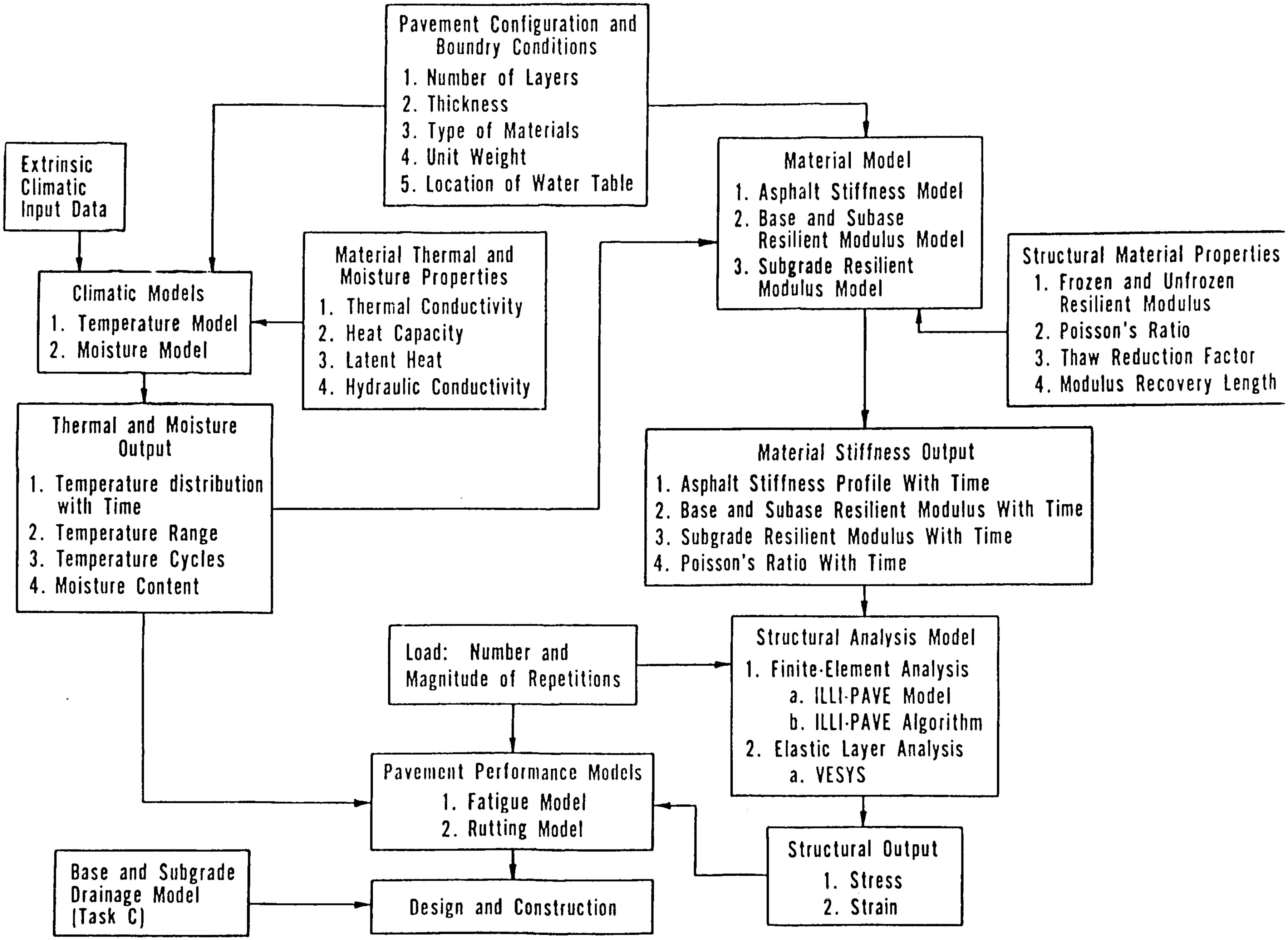


Figure 2.4 CMS Program Incorporated with Structural Analysis and Pavement Performance Models in Design (Ref. 4).

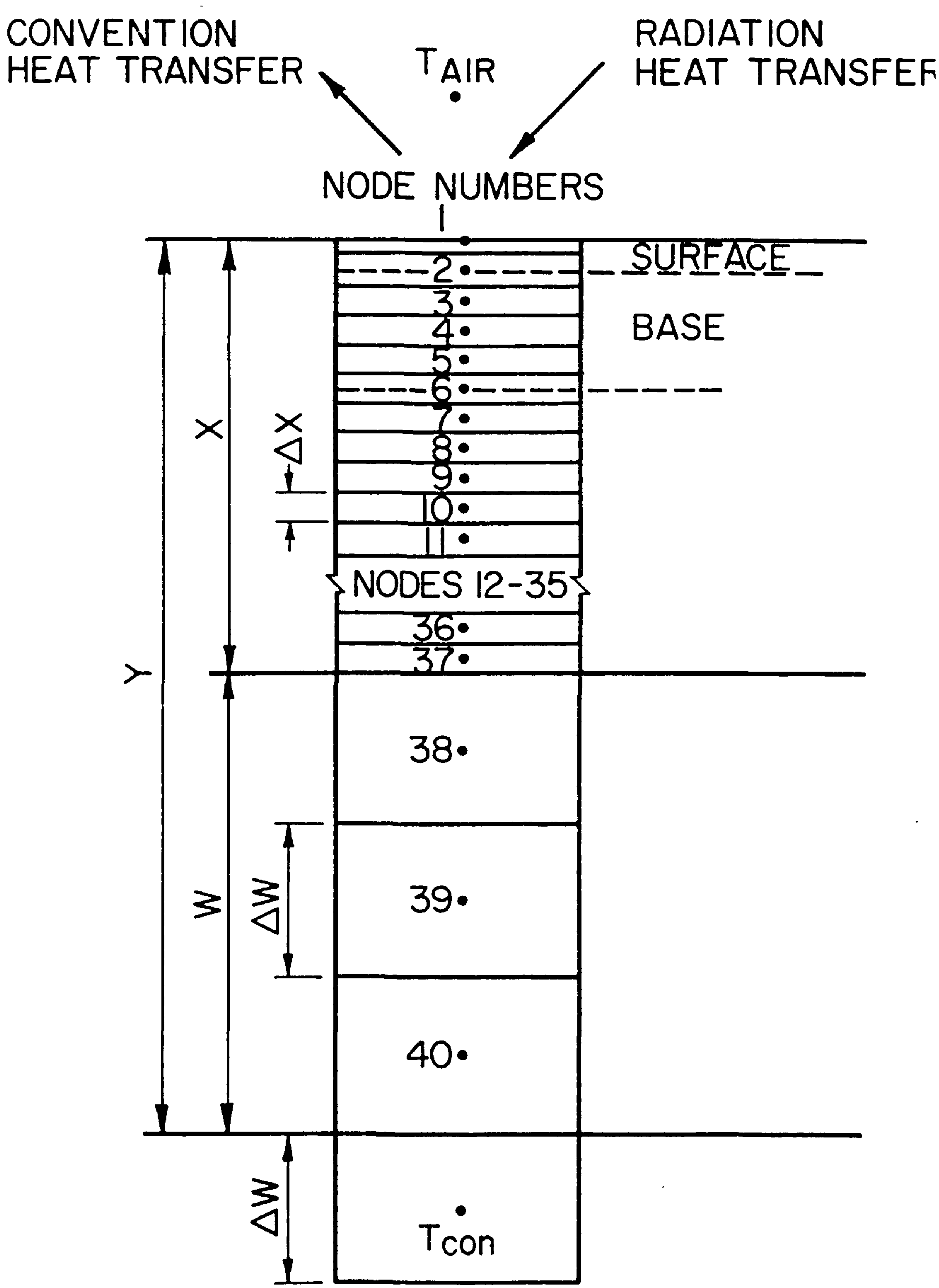


Figure 2.5 The Finite-Difference Pavement System (Ref. 12).

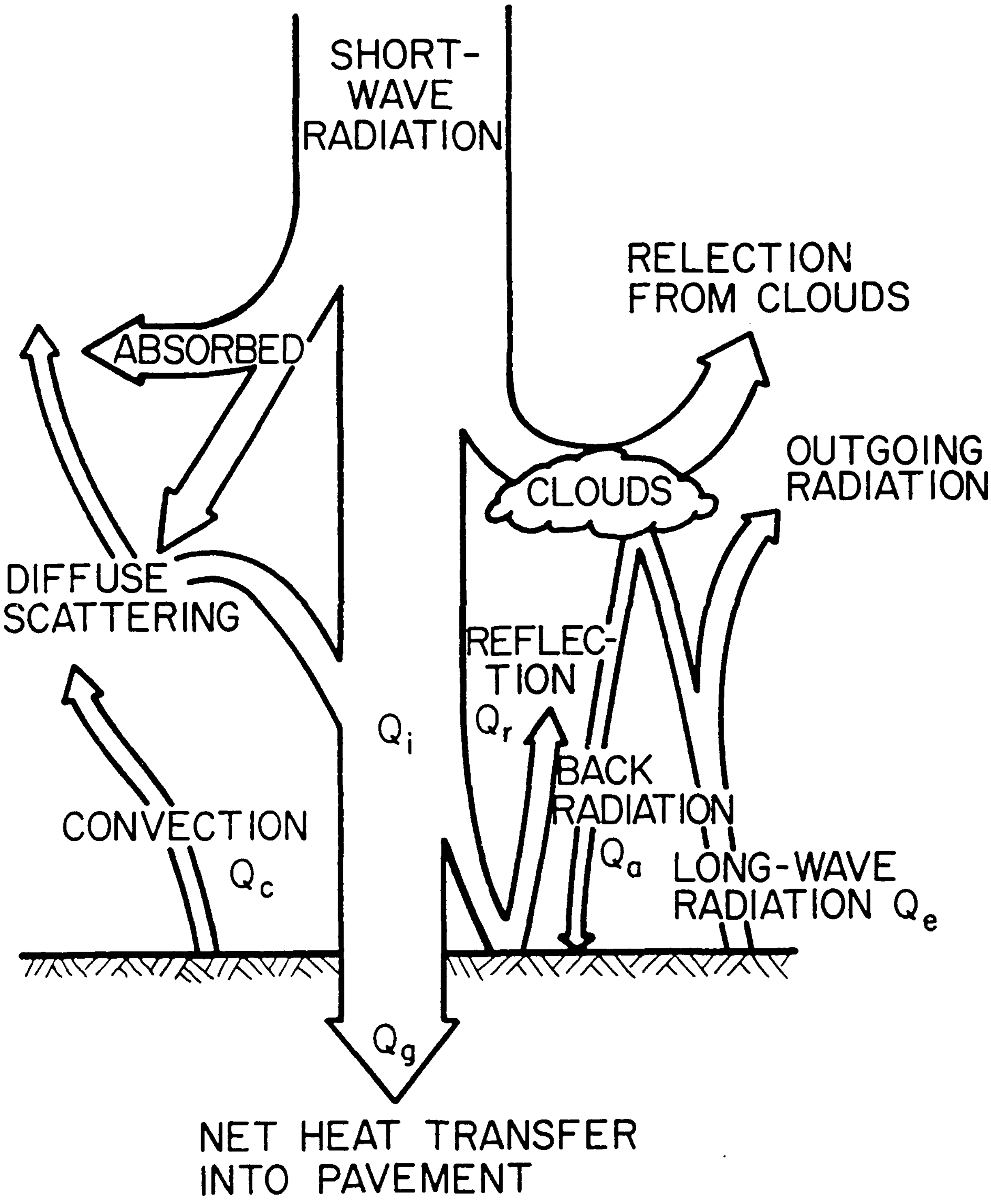


Figure 2.6 Climatic Parameters Which Relate to Radiation and Convection Heat Transfer at a Pavement Surface (Ref. 12).

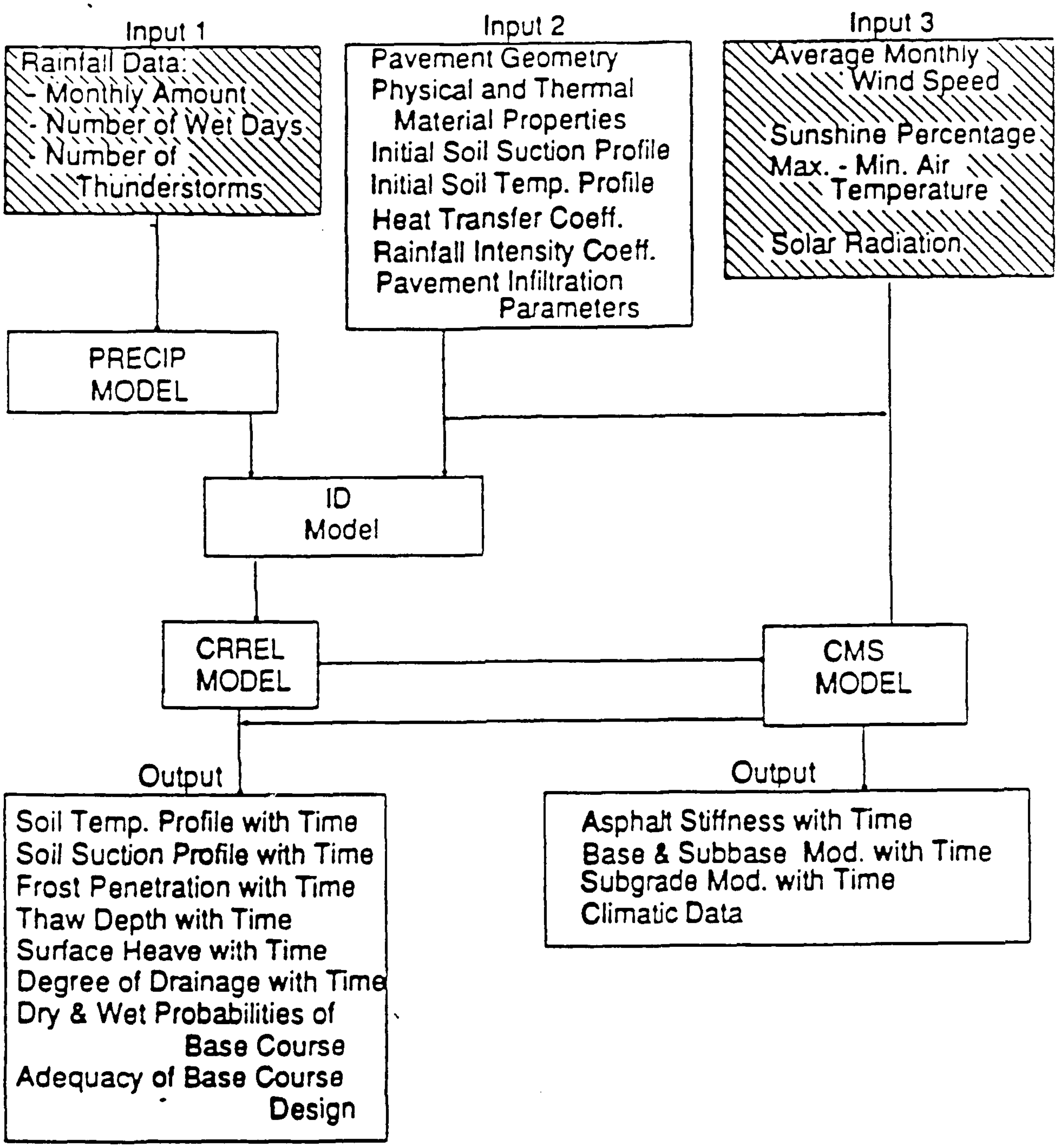


Figure 2.7 Integrated Climatic Model (Ref. 10).

Chapter 3

AIRPORT SURFACE DRAINAGE

3.1 General

The FAA Advisory Circular on Airport Drainage provides reasonably good guidance for the investigation of surface runoff and for the design of structures to control surface water on airports (1). Fowler (2) has presented suggested improvements to the FAA Airport Drainage Circular based on a more recent review. Since it is the purpose of this report to provide guidance for all aspects of airport drainage a comprehensive summary of airport surface drainage as outlined in the FAA Airport Drainage Circular is included.

3.2 Surface Runoff

When designing a functional surface drainage system for an airport, it is first necessary to determine the quantity of surface runoff. Although numerous methods for determining the quantity of rainfall runoff have been developed, the Rational Method remains as the procedure universally applied and recommended by drainage engineers (1). The Rational Method is based on the direct relationship between rainfall and runoff which is expressed by the following equation:

$$Q = C\ I\ A \qquad \text{(Eq. 3.1)}$$

where:

- Q = the runoff in ft^3/sec from a given area,
- C = a runoff coefficient depending upon the character of the drainage area,
- I = the intensity of rainfall in in./hr, and
- A = the drainage area in acres.

The value of the runoff coefficient, C, is based on a study of the soil, the slope and condition of the surface, and the perviousness of the surface. Table 3.1 gives some typical ranges of C values for several different types of surfaces. If several types of surfaces are included in a drainage area under study, the following equation can be used to obtain a composite C value:

$$C_t = \frac{C_1A_1 + C_2A_2 + \ldots + C_nA_n}{A_1 + A_2 + \ldots + A_n} \qquad \text{(Eq. 3.2)}$$

where:

C_t - the composite runoff coefficient of several types of surfaces,

C_n - runoff coefficient of the n^{th} surface

A_n - area in acres of the n^{th} surface, and

n - number of areas being considered.

The value of the rainfall intensity, I, can be determined from relationships such as those shown in Figure 3.1, where intensity of rainfall is plotted against the duration. The rainfall intensity depends upon the period of concentration required for the surface runoff to flow from the most distant point in the area of study to the inlet or point of collection being considered. A return period of 5 years is generally used for design purposes.

The time of concentration is the time at which maximum discharge occurs in the system and the whole area contributes to the flow to the inlet. The time of concentration is composed of "inlet time" and "flow time". The "inlet time" is the time required for the water to flow overland from the most remote point in the drainage area to the inlet being considered. Estimates of the "inlet time" can be obtained from Figure 3.2. However, the formula shown at the top of Figure 3.2 should only be used for distances greater than 800 feet. The "flow time" is the time in which water flows through the drainage system to any point being considered. The "flow time" can be determined by dividing the length of the pipe by the velocity of flow.

3.3 <u>Grading</u>

Proper grading is important in contributing to the success of surface drainage for an airport. Runways and taxiways should be designed with a crown and the slopes beyond the pavement edges should be in agreement with design recommendations. Water should be directed away from the pavements and into areas for collection and disposal, Figure 3.3. To facilitate runoff, a slope of 5 percent should be used next to the pavement edges for a distance of 10 ft. Also, aprons should slope away from buildings so that water, as well as spilt fuel, is directed away from the terminals and concourses. The soil properties and groundwater conditions should be evaluated so that infiltration and erosion potential are included in the surface drainage design.

Before any final computations can be made for the design of the drainage system, a contour map of the airport and the adjacent areas is required, Figure 3.4. The contour interval should be small enough to show all natural watercourses, swales, draws, slopes, ditches, ridges, and drainage structures. Typically, the contour interval is less than 2 ft. Also, a detailed plan which shows the final layout of the runways, taxiways, aprons, and building areas should be made. The finished drawing for these areas require a contour interval of 1 ft or less. The detailed drawings should identify the components of the entire drainage system. This would include labelling each subarea, storm pipelines, direction of flow, pipe sizes, gradients, inlets, manholes, and other drainage components.

3.4 Inlet Location

Inlets are usually located at least 75 ft from the edge of the pavement at major airports and 25 ft from the edge of the pavement at smaller airports which are used exclusively by general aviation. Inlets should not be placed close to the pavement edges for reasons that the flow of water could bypass the inlets and any water which is ponded could back up to the edge of the pavement and saturate the subgrade.

Ponding should be provided around the inlets as temporary storage for runoff from storms which exceed the design storm. Inlets are placed at intermediate low points in the airport and are typically spaced so that the flow from the most remote point of the area is not greater than 400 feet. When several inlets are located in the same graded area, it is customary to place a ridge in between the inlets so that the water does not bypass the upper inlet. Figure 3.5 shows an example of grading to prevent bypass flow in a continuous line of inlets.

3.5 Grates

Grates are used where the surface water is admitted into the drainage system. They may be cast in steel, iron, or ductile iron. Figure 3.6 shows examples of typical grates used in airport drainage. The grates should be strong enough to support the loads from aircraft and maintenance equipment. The number of grates required, as well as the water carrying capacity of the grates, is determined by the depth of head at the grate and the quantity of runoff. The general weir formula is used to calculate the capacity in low head situations. For medium and high heads, the orifice formula is used. These formulas and the relationship between them are described in Figure 3.7.

3.6 Inlet Structures

Figure 3.8 shows examples of inlet design for airport drainage. Inlet structures should be designed so that they do not extend above ground level. They should be 0.1- to 0.2- ft below the ground level to allow for possible settlement around the structure, to permit unobstructed use of the area by airport equipment, and to facilitate entrance of surface water. The backfill around inlets placed in pavements should be compacted with particular care to prevent differential settlement. When placed in rigid pavements, inlets are normally protected by expansion joints placed around their frame.

Inlet structures may be constructed of reinforced concrete, brick, concrete block, precast concrete, or rubble masonry. Whatever material is chosen must be strong enough to withstand those loads associated with airports.

Catch basins are not necessary for airport drainage if the drains are laid on self-cleaning grades. Under certain conditions, they might be necessary to prevent solids and debris from washing into the system.

Manholes are usually placed at all changes in pipe size, grade changes, changes in direction, and junctures of pipe runs for inspection and cleanout purposes. A reasonable interval for spacing of manholes when these changes

are not present is 300- to 500- ft. Where manholes are impractical, drop inlets can be used to allow access for observation and flushing.

Manholes are basically standardized to type and constructed in round, oval, square, or rectangular shapes, Figure 3.9. They are usually made of reinforced concrete, brick, concrete block, precast concrete, corrugated steel, or precast pipe sections. Inside barrel dimensions are commonly 3.5 ft in diameter and 4 ft in height; however, other dimensions may be used to suite a particular situation.

3.7 Drainage Culverts

The design of new culverts and the evaluation of existing culverts on the airport property and in the surrounding area are often necessary in airport drainage work. Culverts are designed to convey water through or under a roadway, runway, taxiway, or other obstruction. The cross-section of a culvert can be circular, oval, elliptical, arch, or box depending on capacity, headroom, and economy. Culverts are generally constructed of steel, aluminum, concrete, and plastic materials. Headwalls are generally cast in place; however, precast and manufactured headwalls are available.

The flow through a culvert involves one of two types of flow; (1) flow with inlet control, or (2) flow with outlet control. If the inlet controls the flow, the cross-sectional area of the culvert, the inlet geometry, and the amount of headwater at the entrance are important factors to consider. The capacity of a culvert with inlet control can be increased by using a rounded, bevelled, or tapered entrance. When the outlet controls the flow, consideration should be given to the elevation of the tailwater in the outlet channel, as well as the roughness, slope, and length of the culvert barrel. The procedures for choosing the type and size of culvert for most conditions can be found elsewhere (3,4,5,6,7,8,9,10).

3.8 Flow In Pipes

After the design runoff for all the subareas has been computed and the locations of the inlets, manholes, pipe runs, and outfalls have been determined, the size and gradient of the pipe drains should be computed. The "flow time" can be calculated for various hydraulic characteristics of the pipe. To determine the flow characteristics in pipes, the most widely used formula is the Manning formula. The formula takes the following form:

$$Q = \frac{1.486\ A\ R^{2/3}\ S^{1/2}}{n} \qquad \text{(Eq. 3.3)}$$

where:

Q = discharge in ft^3/sec,

A = cross-sectional are of flow in ft^2,

R = hydraulic radius in ft which is equal to the area of section/wetted perimeter,

S - slope of pipe invert in ft/ft, and

n - coefficient of roughness of pipe.

Solutions to the Manning formula have been compiled in the form of nomographs as shown in Figures 3.10, 3.11, 3.12, and 3.13 (1). Figures 3.10 through 3.13 can be used to find the size of a pipe which has a coefficient of roughness in the range of 0.012 to 0.031. Some typical roughness coefficients, n, for different pipes are given in Table 3.2. Additional roughness coefficient values have been presented by AISI for storm sewers (11).

To prevent suspended matter from depositing in the pipes, it is important to maintain sufficient velocity within the pipes. A mean velocity of 2.5 ft/sec will usually prevent the depositing of suspended matter in the pipes. When lower velocities are expected in the pipes, care should be taken to construct straight grades and smooth, well constructed joints. Also, pipelines and slopes should be designed so that the velocity of flow will increase progressively or be maintained uniformly from the inlets to the outfalls.

In the past drainage conduits have been constructed of concrete, vitrified clay, corrugated steel, reinforced concrete, corrugated aluminum alloy, asbestos-cement. In recent years, drainage pipes constructed of asbestos-cement have been discontinued and use of pipes manufactured with polymeric materials have increased. The durability of the drainage pipe can be effected by the chemical characteristics of the water or the surrounding soil. Any possible soil-pipe or water-pipe interaction should be investigated. Fuel spillage and solvents can also cause damage to some pipes, especially if they are bituminous coated or in some cases constructed of polymeric materials.

3.9 Loads on Pipes

The structural performance of buried pipe is dependent on the interaction between the soil and pipe. The pipe embedment must be selected for structural as well as drainage characteristics. Structural characteristics of the embedment include consideration of the dimensions of the excavation around the pipe, soil type, compaction density, depth of pipe burial, and the height and behavior of the water table. The required dimensions, soil type, and compaction density of the embedment are dependent on the pipe stiffness. Flexible pipes, such as plastic and corrugated metal, utilize the embedment materials to transfer vertical loads into the adjacent soil. Rigid pipe, such as concrete and clay, transfer vertical loads directly into the bedding with minimal load transfer into the adjacent soil. Therefore, the required structural characteristics of the embedment varies with the type of pipe and should be accomplished in accordance with appropriate design standards. Table 3.3 shows typical pipe cover depths recommended in the FAA Airport Drainage Circular for flexible pavement systems (1). Acceptable design practices for using various types of pipe are available elsewhere in the literature (7,12,13,14).

3.10 Flow In Open Channels

The Manning formula can be applied to open channel flow as well as to flow in conduits. Maximum use of open channels is encouraged to take advantage of their low cost and large water carrying capacity. Channels should be free from excess maintenance which could result from erosion, silting, or steep backslopes. Table 3.4 contains roughness coefficients for open channels. Figure 3.14 shows a nomograph solution of the Manning formula and Figures 3.15 through 3.20 permit a quick solution to ordinary channel problems that involve channels with various shapes which may be trapezoidal, triangular, and parabolic.

Channels lined with vegetation introduce a vegetal retardance element, which is a function of the turf characteristics and the depth and velocity of flow. This retardance element varies with the product of velocity and hydraulic radius. Figure 3.21 can be used to obtain a retardance or roughness coefficient for different lengths of grass once the hydraulic radius, channel slope, and the grass coefficient are known.

3.11 Ponding

The rate of outflow from a drainage area is controlled by the capacity of the drainage structure or drainpipe serving the area. Ponding occurs when the rate of runoff at an inlet or drainpipe exceeds the drain capacity. The elevation of water at the inlet effects the rate of outflow from the ponding basin. The rate will increase as the head at the inlet increases.

The main objective of ponding is to control the water level in the pond and to dispose of the water as soon as possible. It is important that the ponded water does not effect airport operation or safety. Turfed areas should be drained rather quickly so that vegetation will not be destroyed by standing water.

3.12 Summary

Many of the important considerations for airport drainage which are included in the FAA Advisory Circular have been summarized in this chapter of the report (1). This report section is not intended to replace the information in the FAA Advisory Circular on Airport Drainage, but to highlight the important points and call attention to those airport drainage factors which must be evaluated when considering total airport drainage design.

REFERENCES

1. Airport Drainage, AC150/5320-5B, Department of Transportation, Federal Aviation Administration, Washington, D. C., 1970.

2. Fowler, J., "Improvements to Airport Drainage Criteria, Phase I," Report No. FAA-RD-76-59, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 1976.

3. "Drainage for Areas Other Than Airfields," Technical Manual TM 5-820-4, Department of the Army, 1965.

4. "Hydraulic Charts for the Selection of Highway Culverts," Hydraulic Engineering Circular No. 5, Bureau of Public Roads, 1965.

5. "Capacity Charts for the Hydraulic Design of Highway Culverts," Hydraulic Engineering Circular No. 10, Bureau of Public Roads, 1965.

6. "Design Data, Loads and Supporting Strengths, Hydraulics of Sewers, Hydraulics of Culverts, Installation, and Miscellaneous," American Concrete Pipe Association, 1968-1969.

7. "Concrete Pipe Design Manual," American Concrete Pipe Association, Vienna, VA., 1985.

8. "Hydraulics of Culverts," American Concrete Pipe Association, 1964.

9. "Handbook of Steel Drainage and Highway Construction Products," American Iron and Steel Institute, 1967.

10. Harvey, G. G., "Plastic Pipe in Airport Drainage Systems," Report No. FAA-RD-77-38, U. S. Army Engineering Waterways Experiment Station, Vicksburg, MS., 1977.

11. "Modern Sewer Design," American Iron and Steel Institute, 1980.

12. Standard Specifications for Highway Bridges," American Association of State Highway and Transportation Officials, Washington, D.C., 1983.

13. "Clay Pipe Engineering Manual," National Clay Pipe Institute, Washington, D.C., 1978.

14. "Gravity Sanitary Sewer Design and Construction," Manual No. 60, American Society of Civil Engineers, New York, NY, 1982.

Table 3.1 Runoff Coefficients for Different Surface Types (Ref. 1).

Type of surface	Factor "C"
For all watertight roof surfaces	.75 to .95
For asphalt runway pavements	.80 to .95
For concrete runway pavements	.70 to .90
For gravel or macadam pavements	.35 to .70
For impervious soils (heavy)*	.40 to .65
For impervious soils, with turf*	.30 to .55
For slightly pervious soils*	.15 to .40
For slightly pervious soils, with turf*	.10 to .30
For moderately pervious soils*	.05 to .20
For moderately pervious soils, with turf*	.00 to .10

*For slopes from 1 percent to 2 percent.

Table 3.2 Typical Roughness Coefficients for Pipe.

Conduit Material	Manning "n"
Corrugated Plastic Tubing:	
a. 3" - 8" (75mm-200mm) diameters	0.014-0.016
b. 10" - 12" (250mm-300mm) diameters	0.016-0.018
c. Larger than 12" (300mm) diameter	0.019-0.021
Concrete pipe	0.011-0.014
Corrugated Metal Pipe 1/2-in. x 2-2/3-in. (12.5m x 66.7mm), Corrugations, Plain Annular Corrugations	0.022-0.026

NOTE: Corrugated metal pipes with helical corrugations may have lower n-values than shown for annular corrugated pipe.

Clay Drain Tile	0.011-0.014
Ductile Iron Pipe (Cement Lined)	0.011-0.014
Plastic Pipe (Smooth Interior)	0.010-0.013
Spiral Rib Metal Pipe	0.012-0.015

This table provides recommended Manning's "n" values for estimating internal volume flow rates for the materials listed. Actual pipline performance depends upon the effects of abrasion, corrosion, deflection, alignment, joint conditions, and flow velocity.

Table 3.3 Minimum Depth of Cover in Feet for Pipe Under Flexible Pavement (Ref. 1).

CORRUGATED ALUMINUM 2 2/3" x 1/2" or 2" x 1/2" CORRUGATIONS

AIRCRAFT WHEEL LOAD—Up to 30,000 lb. single and up to 40,000 lb. dual

Metal thickness (in.)	Pipe diameter (in.) 12	18	24	36	48	60	72	84	96
0.060	2.0	2.5	2.5						
0.075	1.5	2.0	2.5	2.5	3.0				
0.105		1.5	1.5	1.5	2.0	2.5	3.0		
0.135			1.0	1.0	1.5	1.5	1.5		
0.165					1.0	1.5	1.5	2.0	2.0

AIRCRAFT WHEEL LOAD—40,000 lb. dual to 110,000 lb. dual

Metal thickness (in.)	Pipe diameter (in.) 12	18	24	36	48	60	72	84	96
0.060	2.0	2.5	2.5						
0.075	1.5	2.0	2.5	2.5	3.0				
0.105		1.5	1.5	1.5	2.0	2.5	3.0		
0.135				1.5	1.5	2.0	2.5	3.0	
0.165					1.5	1.5	2.0	2.0	2.5

AIRCRAFT WHEEL LOAD—110,000 lb. dual to 200,000 lb. dual; 190,000 lb. dt. to 350,000 lb. dt; up to 750,000 lb. ddt & 1,500,000 lb

Metal thickness (in.)	Pipe diameter (in.) 12	18	24	36	48	60	72	84	96
0.060	3.0	3.0	3.0						
0.075	3.0	3.0	3.0	3.5	5.0				
0.105		2.0	2.0	2.5	3.5	4.5			
0.135				2.0	3.0	4.0	4.5	5.5	
0.165					2.5	3.5	4.0	5.0	5.5

CORRUGATED ALUMINUM 6" x 1" CORRUGATIONS

AIRCRAFT WHEEL LOAD—up to 30,000 lb. single and up to 40,000 lb. dual

Metal thickness (in.)	Pipe diameter (in.) 36	48	60	72	84	96	108	120
0.060	2.0	2.0	2.5	3.0				
0.075	1.0	1.5	2.0	2.5	3.5			
0.105	1.0	1.0	1.5	2.0	3.0	3.5		
0.135			1.5	[illegible]	2.5	3.0	4.0	
0.165					2.0	2.5	3.5	4.5

AIRCRAFT WHEEL LOAD—40,000 lb. dual to 110,000 lb. dual

Metal thickness (in.)	Pipe diameter (in.) 36	48	60	72	84	96	108	120
0.060	2.5	3.0	3.5	4.0				
0.075	1.5	2.0	2.5	3.0	4.0			
0.105	1.5	1.5	2.0	2.5	3.5	4.0		
0.135			2.0	2.5	3.0	3.5	4.5	
0.165					2.5	3.0	4.0	5.0

AIRCRAFT WHEEL LOAD—110,000 lb. d. to 200,000 lb. d; 190,000 lb. dt. to 350,000 lb. dt.; up to 750,000 lb. ddt. & 1,500,000 lb.

Metal thickness (in.)	Pipe diameter (in.) 36	48	60	72	84	96	108	120
0.060	4.0	4.5	5.0	5.0				
0.075	3.0	3.5	3.5	4.0	4.0			
0.105	2.0	2.0	3.0	2.5	4.0	4.5		
0.135			2.5	3.0	3.5	4.0	5.0	
0.165					3.0	3.5	4.5	5.5

CLAY

AIRCRAFT WHEEL LOAD—up to 30,000 lb. single and up to 40,000 lb. dual

Pipe type	Pipe diameter (in.) 6	10	12	15	18	21	24	30	36
Std. strength clay	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Extra strength clay	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

AIRCRAFT WHEEL LOAD—40,000 lb. dual to 110,000 lb. dual

Pipe type	Pipe diameter (in.) 6	10	12	15	18	21	24	30	36
Std. strength clay	4.0	5.5	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Extra strength clay	2.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5

ASBESTOS CEMENT

AIRCRAFT WHEEL LOAD—up to 30,000 lb. single and up to 40,000 lb. dual

Asbestos cement-class	Pipe diameter (in.) 6	10	12	16	18	24	30	36	42
1500	2.5	2.5	2.5	2.5					
2400	2.5	2.5	2.5	2.5	2.5	2.5			
3300	1.5	1.5	1.5	1.5	1.5	1.5	1.5		
4000		1.5	1.5	1.5	1.5	1.5	1.5	1.5	
5000		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
6000								1.0	1.0
7000								1.0	1.0

AIRCRAFT WHEEL LOAD—40,000 lb. dual to 110,000 lb. dual

Asbestos cement-class	Pipe diameter (in.) 6	10	12	16	18	24	30	36	42
1500	5.5	5.5	5.5	5.5					
2400	6.0	6.0	6.0	6.0	6.0	6.0			
3300	3.5	3.5	3.5	3.5	3.5	3.5			
4000		3.5	3.5	3.5	3.5	3.5	3.5	3.5	
5000		3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
6000								2.5	2.5
7000								2.5	2.5

Table 3.3 Continued

CORRUGATED STEEL 2 2/3" x 1/2" CORRUGATIONS

AIRCRAFT WHEEL LOAD—Up to 30,000 lb. single and up to 40,000 lb. dual

Metal thickness (in.)	Pipe diameter (in.) 12	18	24	36	48	60	72	84	96
0.052	1.0	1.0	1.5	1.5					
0.064	1.0	1.0	1.0	1.5	1.5				
0.079	1.0	1.0	1.0	1.5	1.5	1.5			
0.109			1.0	1.0	1.0	1.0	1.5		
0.138				1.0	1.0	1.0	1.0	1.5	
0.168				1.0	1.0	1.0	1.0	1.5	1.5

AIRCRAFT WHEEL LOAD—40,000 lb. dual to 110,000 lb. dual

Metal thickness (in.)	Pipe diameter (in.) 12	18	24	36	48	60	72	84	96
0.052	1.5	2.0	2.0	2.5					
0.064	1.5	1.5	2.0	2.5	2.5				
0.079	1.5	1.5	2.0	2.5	2.5	2.5			
0.109			1.5	2.0	2.0	2.0	2.5		
0.138				2.0	2.0	2.0	2.0	2.5	
0.168				2.0	1.5	2.0	2.0	2.0	2.5

AIRCRAFT WHEEL LOAD—110,000 lb. dual to 200,000 lb. dual; 190,000 lb. dt. to 350,000 lb. dt.; up to 750,000 lb. ddt.

Metal thickness (in.)	Pipe diameter (in.) 12	18	24	36	48	60	72	84	96
0.052	2.0	2.5	3.0	3.0					
0.064	2.0	2.5	2.5	3.0	3.0				
0.079	2.0	2.0	2.5	2.5	2.5	3.0			
0.109			2.0	2.5	2.5	2.5	3.0		
0.138				2.0	2.0	2.5	3.0	3.0	
0.168				2.0	2.0	2.5	3.0	3.0	3.0

AIRCRAFT WHEEL LOAD—Up to 1,500,000 lb.

Metal thickness (in.)	Pipe diameter (in.) 12	18	24	36	48	60	72	84	96
0.052	2.5	2.5	3.0	3.0					
0.064	2.5	2.5	2.5	3.0	3.0				
0.079	2.5	2.5	2.5	2.5	2.5	3.0			
0.109			2.5	2.5	2.5	2.5	3.0		
0.138				2.5	2.5	2.5	3.0	3.0	
0.168					2.5	2.5	3.0	3.0	3.0

CORRUGATED STEEL 3" x 1" CORRUGATIONS

AIRCRAFT WHEEL LOAD—Up to 30,000 lb. single and up to 40,000 lb. dual

Metal thickness (in.)	Pipe diameter (in.) 36	48	60	72	84	96	108	120
0.052	1.5	2.0	2.0	2.0				
0.064	1.0	1.5	1.5	2.0	2.0	2.0		
0.079	1.0	1.0	1.5	1.5	2.0	2.0	2.0	
0.109	1.0	1.0	1.0	1.0	1.5	1.5	2.0	2.0
0.138	1.0	1.0	1.0	1.0	1.0	1.5	2.0	2.0
0.168	1.0	1.0	1.0	1.0	1.0	1.5	2.0	2.0

AIRCRAFT WHEEL LOAD—40,000 lb. dual to 110,000 lb. dual

Metal thickness (in.)	Pipe diameter (in.) 36	48	60	72	84	96	108	120
0.052	2.5	3.0	3.0	3.0				
0.064	2.0	2.5	2.5	3.0	3.0	3.0		
0.079	1.5	2.0	2.5	2.5	3.0	3.0	3.0	
0.109	1.5	1.5	2.0	2.0	2.0	2.5	3.0	3.0
0.138	1.5	1.5	1.5	2.0	2.0	2.0	2.5	2.5
0.168	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.5

AIRCRAFT WHEEL LOAD—110,000 lb. dual to 200,000 lb. dual; 190,000 lb. dt. to 350,000 lb. dt; up to 750,000 lb. ddt.

Metal thickness (in.)	Pipe diameter (in.) 36	48	60	72	84	96	108	120
0.052	3.0	3.5	3.5					
0.064	2.5	3.0	3.5	3.5	3.5			
0.079	2.0	2.5	3.0	3.0	3.5	3.5		
0.109	2.0	2.0	2.5	2.5	3.0	3.5	3.5	3.5
0.138	2.0	2.0	2.0	2.5	3.0	3.0	3.5	3.5
0.168	2.0	2.0	2.0	2.0	2.5	2.5	3.0	3.0

AIRCRAFT WHEEL LOAD—Up to 1,500,000 lb.

Metal thickness (in.)	Pipe diameter (in.) 36	48	60	72	84	96	108	120
0.052	3.0	3.5	3.5					
0.064	2.5	3.0	3.5	3.5	3.5			
0.079	2.5	2.5	3.0	3.0	3.5	3.5		
0.109	2.5	2.5	2.5	2.5	3.0	3.5	3.5	3.5
0.138	2.5	2.5	2.5	2.5	3.0	3.0	3.5	3.5
0.168	2.5	2.5	2.5	2.5	2.5	2.5	3.0	3.0

STRUCTURAL PLATE PIPE—9" x 2 1/2" CORR. FOR ALUMINUM; 6" x 2" CORRUGATIONS FOR STEEL

AIRCRAFT WHEEL LOAD—Up to 30,000 lb. s. or 40,000 lb. d.	AIRCRAFT WHEEL LOAD—40,000 lb. d. to 110,000 lb. d.	AIRCRAFT WHEEL LOAD—110 k.d. to 200k.d.; 190 k d.t. to 350 k. d.t.; to 750 k. d.d.t.	AIRCRAFT WHEEL LOAD—Up to 1,500,000 lb.
Pipe dia.÷8 but not less than 1.0'	Pipe dia÷6 but not less than 1.5'	Pipe dia.÷5 but not less than 2.0'	Pipe dia÷4 but not less than 2.5'

Table 3.3 Continued

NONREINFORCED CONCRETE

AIRCRAFT WHEEL LOAD—Up to 30,000 lb. single and up to 40,000 lb. dual

Pipe type	Pipe diameter (in.) 4	6	8	10	12	15	18	21	24
Std. strength	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5
Extra strength	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5

AIRCRAFT WHEEL LOAD—40,000 lb. dual to 110,000 lb. dual

Pipe type	Pipe diameter (in.) 4	6	8	10	12	15	18	21	24
Std. strength	3.5	4.0	4.0	4.5	5.5	6.0	6.0	6.0	6.0
Extra strength	1.5	2.0	2.5	3.0	3.5	3.5	3.5	3.5	3.5

REINFORCED CONCRETE

AIRCRAFT WHEEL LOAD—Up to 30,000 lb. single and up to 40,000 lb. dual

Reinf. concrete 0.01" crack D-load	Pipe diameter (in.) 12	15	18	21	24	27	30	33	36	42	48	54	60	72	84	96	108	120	132	144
800													1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1000	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1350	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2000	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3000	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

AIRCRAFT WHEEL LOAD—40,000 lb. dual to 110,000 lb. dual

Reinf. concrete 0.01" crack D-load	Pipe diameter (in.) 12	15	18	21	24	27	30	33	36	42	48	54	60	72	84	96	108	120	132	144
800													6.5	5.5	4.5	3.5	2.0	1.5	1.5	1.0
1000	5.5	5.5	5.5	5.5	5.5	5.0	5.0	5.0	4.5	4.5	4.0	4.0	3.5	3.0	2.0	1.5	1.0	1.0	1.0	1.0
1350	4.0	4.0	4.0	4.0	3.5	3.5	3.5	3.5	3.0	3.0	2.5	2.0	2.0	1.5	1.0	1.0	1.0	1.0	1.0	1.0
2000	3.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3000	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

AIRCRAFT WHEEL LOAD—110,000 lb. dual to 200,000 lb. dual; 190,000 lb. dual tandem to 350,000 lb. dual tandem; up to 750,000 lb. d.d.t.

Reinf. concrete 0.01" crack D-load	Pipe diameter (in.) 12	15	18	21	24	27	30	33	36	42	48	54	60	72	84	96	108	120	132	144
800																				
1000																				
1350	7.0	7.0	7.0	7.0	7.0	6.5	6.5	6.5	6.0	6.0	6.0	6.0	6.0	6.0	6.0	5.5	5.5	5.0	4.5	4.0
2000	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.5	3.5	3.0	2.5	2.0	2.0	2.5	2.5	2.0	2.0	2.0	1.5
3000	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.0	1.0	1.0	1.5	1.5	1.0	1.0	1.0	1.0

AIRCRAFT WHEEL LOAD—Up to 1,500,000 lb.

Reinf. concrete 0.01" crack D-load	Pipe diameter (in.) 12	15	18	21	24	27	30	33	36	42	48	54	60	72	84	96	108	120	132	144
2000	7.0	7.0	7.0	7.0	7.0	6.5	6.5	6.5	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
3000	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0

1. Cover depths are measured from top of flexible pavement, however, provide at least 1 foot between bottom of pavement structure and top of pipe.
2. The types of pipe shown are available in intermediate sizes, such as 6", 8", 15", 27", 33", etc.
3. For pipe installation in turfed areas use cover depths shown for 30,000 pound single; 40,000 pound dual.
4. Cover depths shown *do not provide for freezing* conditions. Usually the pipe invert should be below maximum frost penetration.
5. Blanks in tables indicate that pipe will not meet strength requirements.
6. Minimum cover depths shown for flexible pipe are based on use of excellent backfill.
7. Minimum cover depths shown for rigid pipe are based on use of class B bedding.
8. Minimum cover requirements for concrete arch or elliptical pipe may be taken from tables for reinforced concrete circular pipe, providing the outside horizontal span of the arch or elliptical pipe is matched to outside diameter of the circular pipe (assumes that classes of the pipes are the same).
9. Pipe cover requirements for "up to 1,500,000 pounds" are theoretical as gear configuration is not known.

RIGID PAVEMENT

For all types and sizes of pipe use 1.5 foot as minimum cover under rigid pavement (measure from bottom of slab, providing pipe is kept below subbase course). Rigid pipe for loads categorized as "up to 1,500,000 lb." must, however, be either class IV or class V reinforced concrete.

Table 3.4 Roughness Coefficients for Open Channels (Ref. 1).

OPEN CHANNELS

	Maximum Permissible Velocity in Feet/Second	*Coeffic. "n"*
Paved		
Concrete	20 to 30+	0.011 to 0.020
Asphalt	12 to 15+	0.013 to 0.017
Rubble or Riprap	20 to 25	0.017 to 0.030
Earth		
Bare, sandy silt, weathered	2.0	0.020
Silt clay or soft shale	3.5	0.020
Clay	6.0	0.020
Soft sandstone	8.0	0.020
Clean gravelly soil	6.0	0.025
Natural earth, with vegetation	6.0	0.030 to 0.150*
Turf		
Shallow flow	6.0	0.06 to 0.08
Depth of flow over 1 foot	6.0	0.04 to 0.06

*Will vary with straightness of alignment, smoothness of bed and side slopes, and whether channel has light vegetation or is choked with weeds and brush.

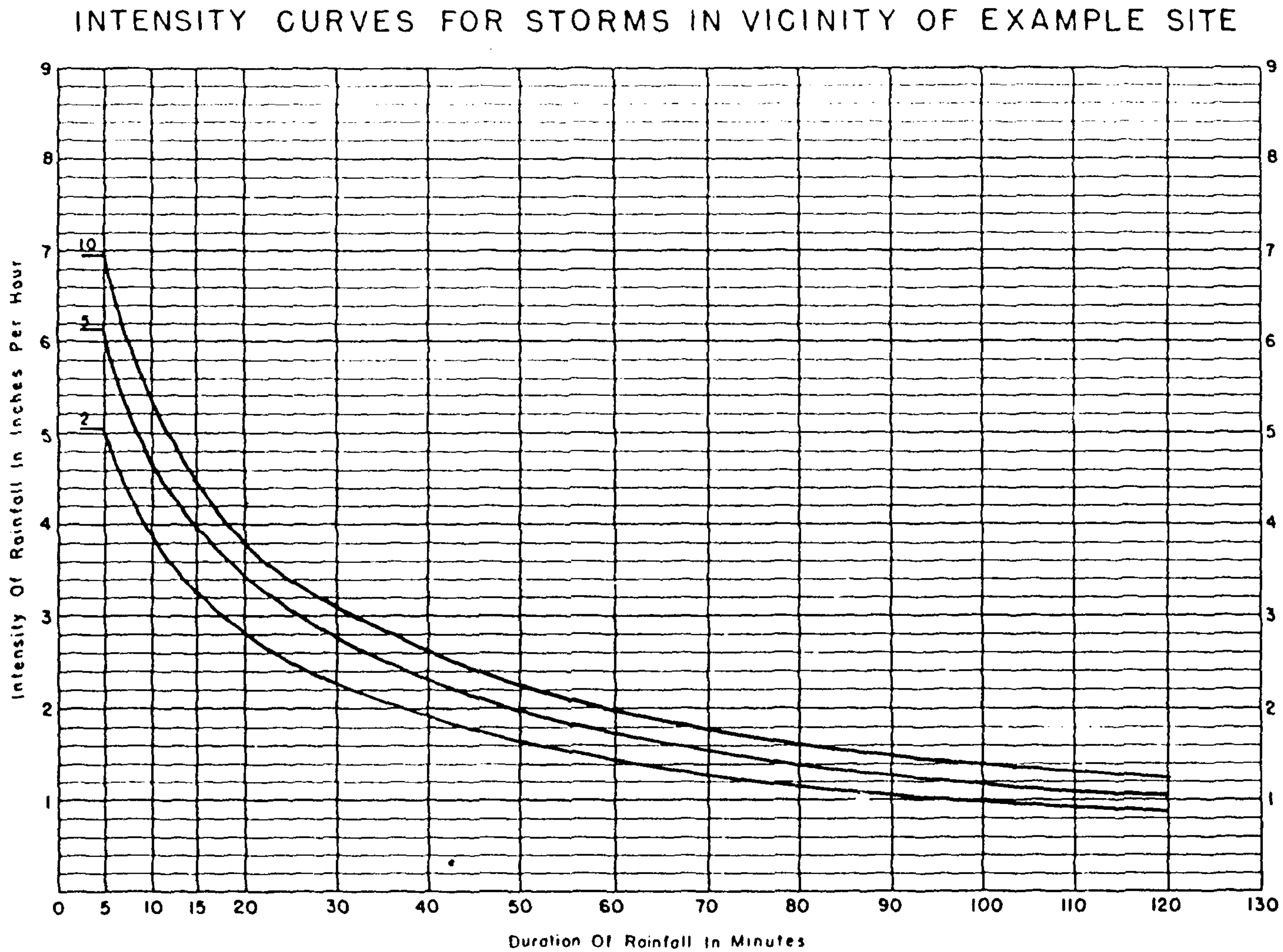


Figure 3.1 Relationship Between Rainfall Intensity and Duration (Ref. 1).

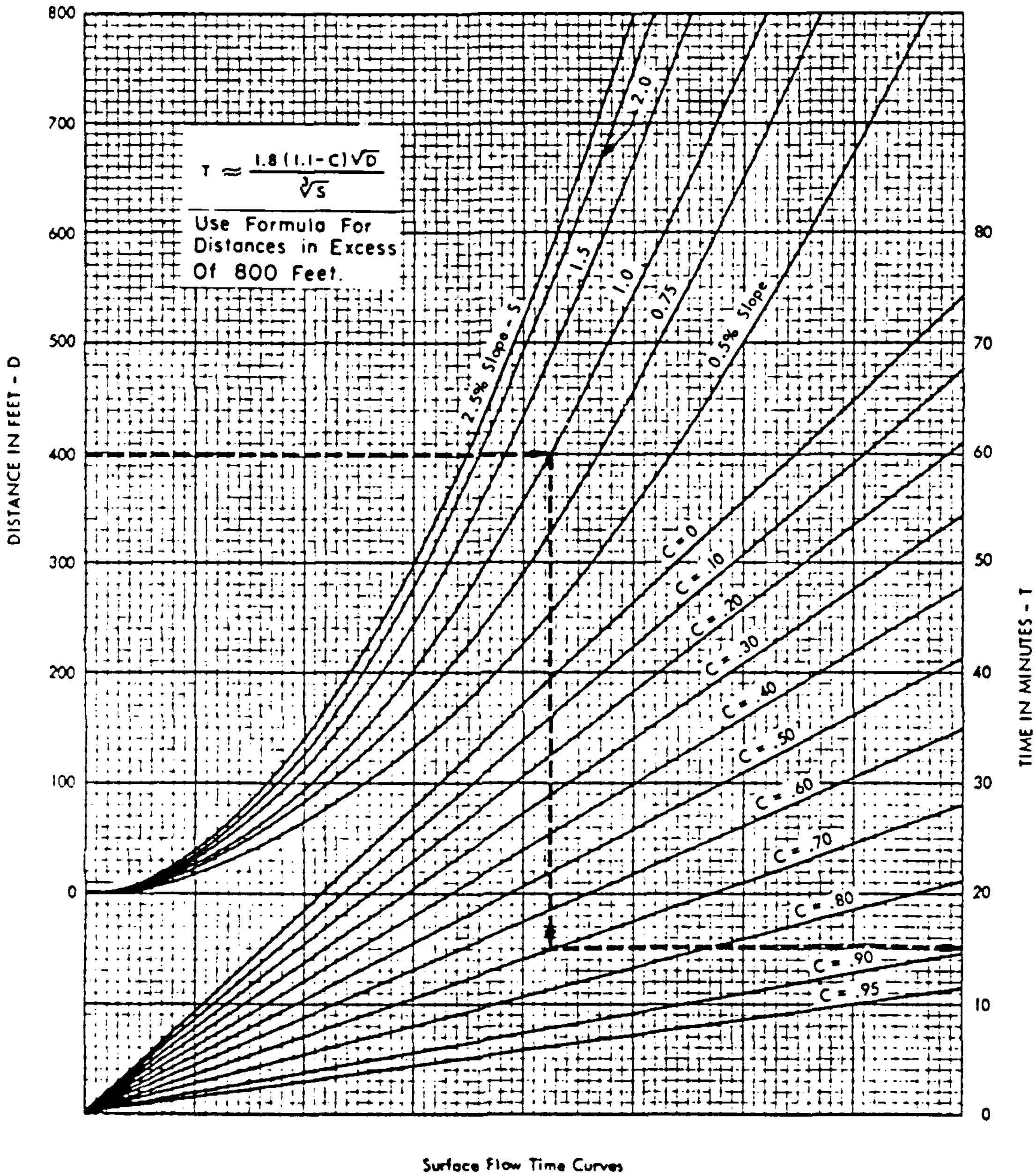


Figure 3.2 Surface Flow Time Curves (Ref. 1).

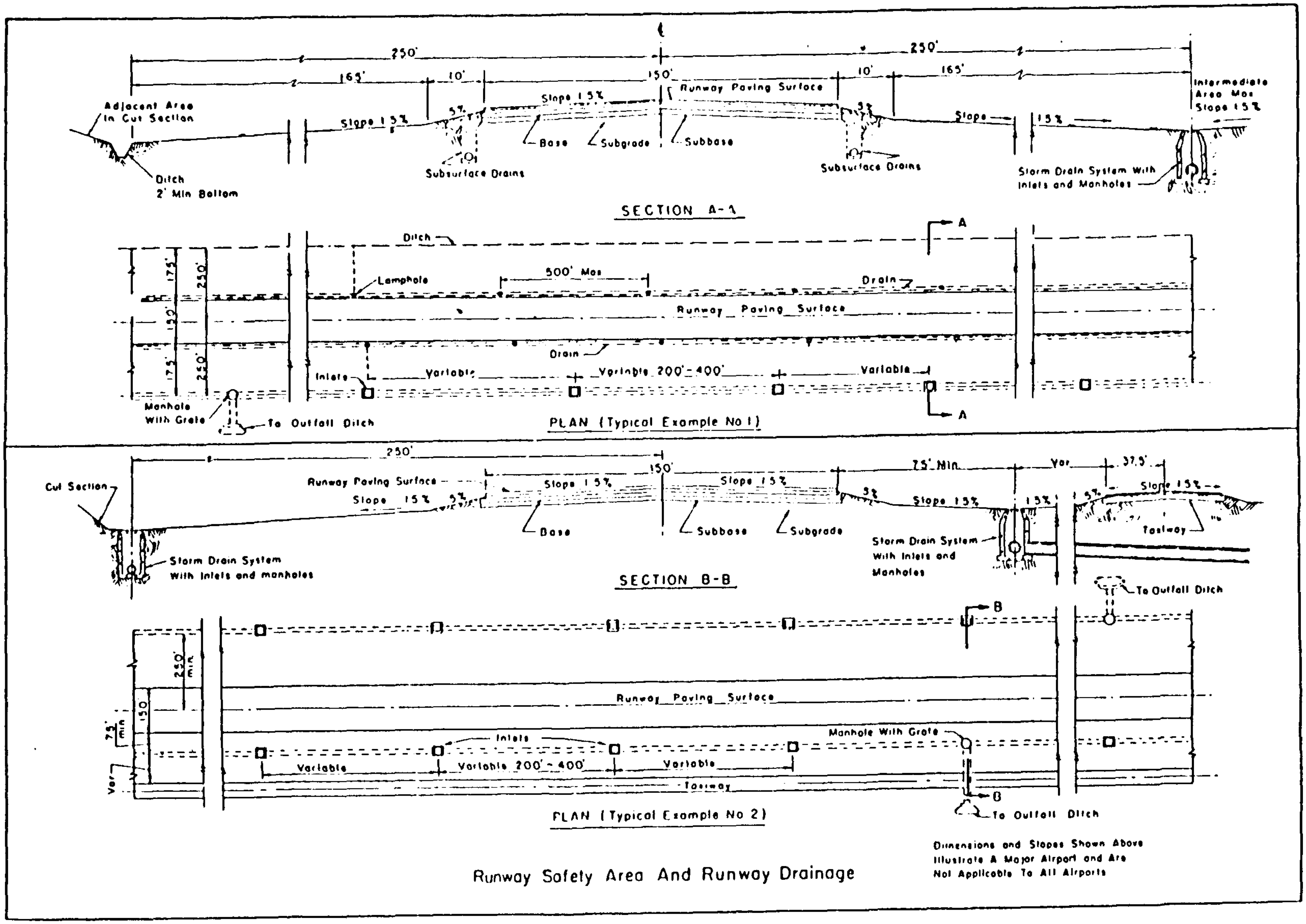


Figure 3.3 Runway Safety Area and Runway Drainage (Ref. 1).

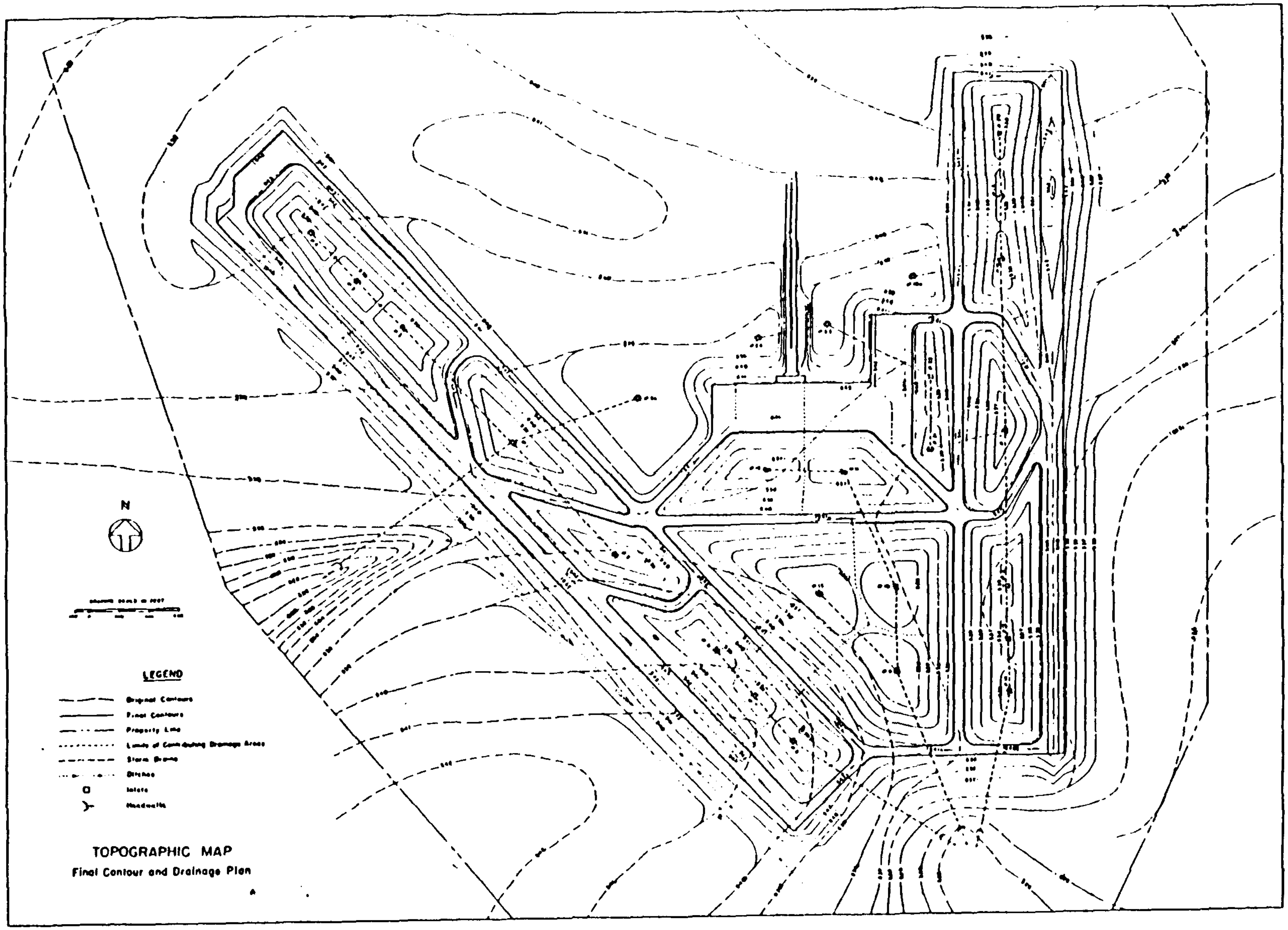


Figure 3.4 Typical Topographic Map Showing Contours (Ref. 1).

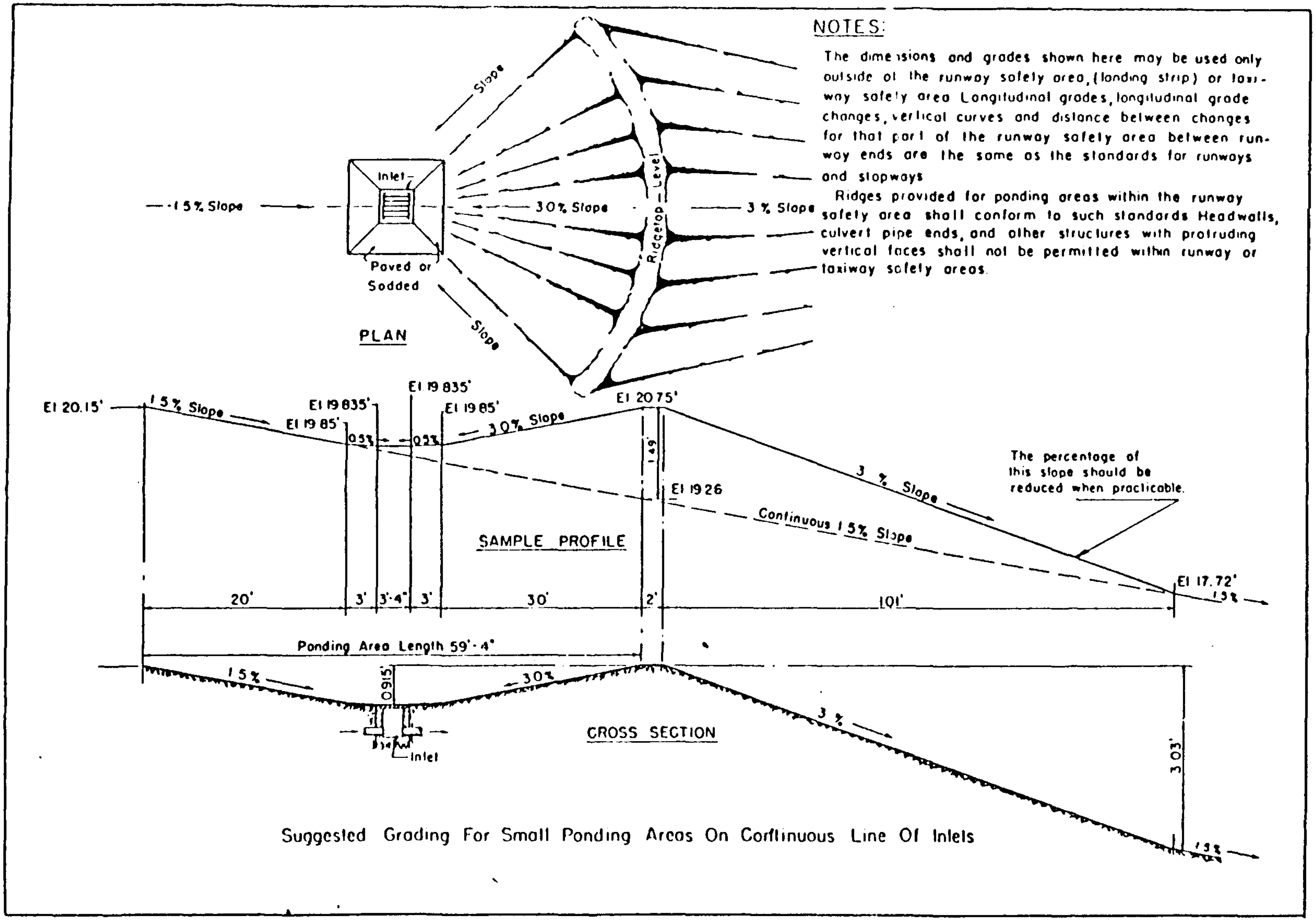


Figure 3.5 Grading Procedure to Prevent Flow Bypass in a Continuous Line of Inlets (Ref. 1).

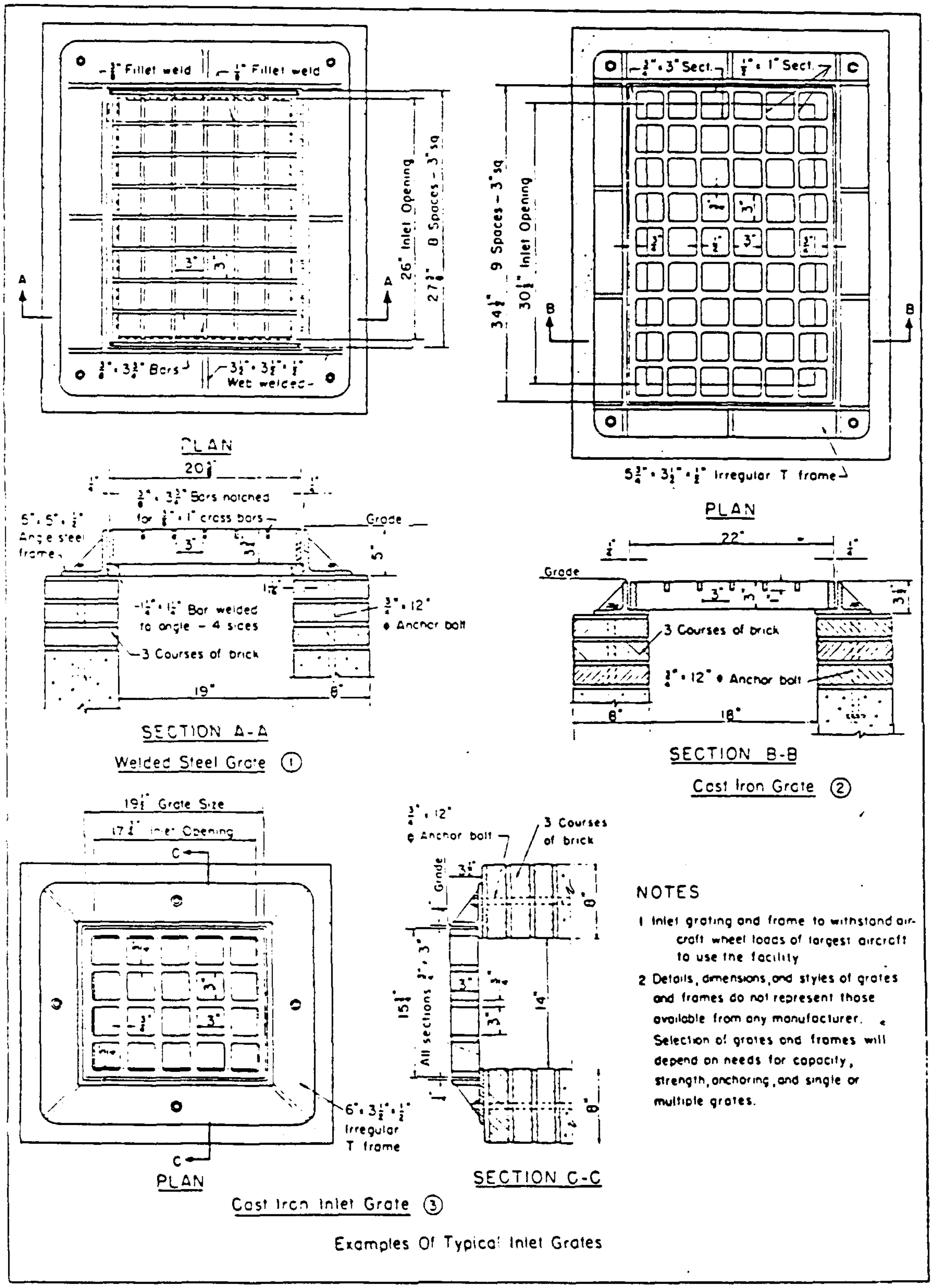
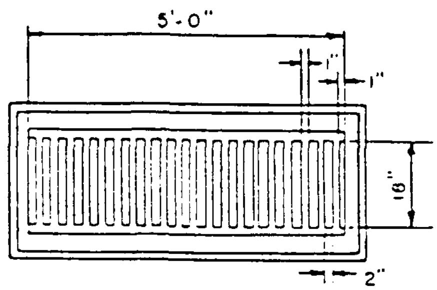


Figure 3.6 Typical Inlet Grates (Ref. 1).



TYPICAL PLAN OF DOUBLE INLET GRATING

WATERWAY OPENING = 5.0 SQ. FT. (DOUBLE GRATING)

ASSUME GRATING IS PLACED SO THAT FLOW WILL OCCUR FROM ALL SIDES OF INLET. FOR LOW HEADS DISCHARGE WILL CONFORM WITH GENERAL WEIR EQUATION.

$Q = CLH^{3/2}$

WHERE

$C = 3.0$

L = 13.0 FT GROSS PERIMETER OF GRATE OPENING (OMITTING BARS) FOR GRATE ILLUSTRATED

H = HEAD IN FEET

FOR HIGH HEADS DISCHARGE WILL CONFORM WITH ORIFICE FORMULA:

$Q = CA\sqrt{2gH}$

WHERE

$C = 0.6$

A = 5.0 SQ. FT.

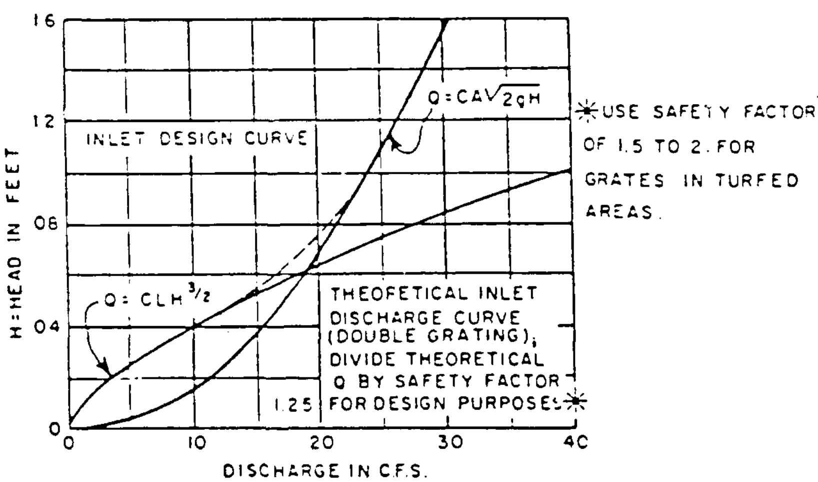
g = ACCELERATION OF GRAVITY IN FEET PER SECOND^2

H = HEAD IN FEET

THEORETICAL DISCHARGE RELATION TO BE MODIFIED BY 1.25 SAFETY FACTOR

COEFFICIENTS BASED ON MODEL TEST OF SIMILAR GRATES WITH RATIO:

NET WIDTH OF GRATE OPENING TO GROSS WIDTH = 2:3



DETERMINATION OF TYPICAL INLET GRATING DISCHARGE CURVE

Figure 3.7 Typical Inlet Grating Discharge Relationships (Ref. 1).

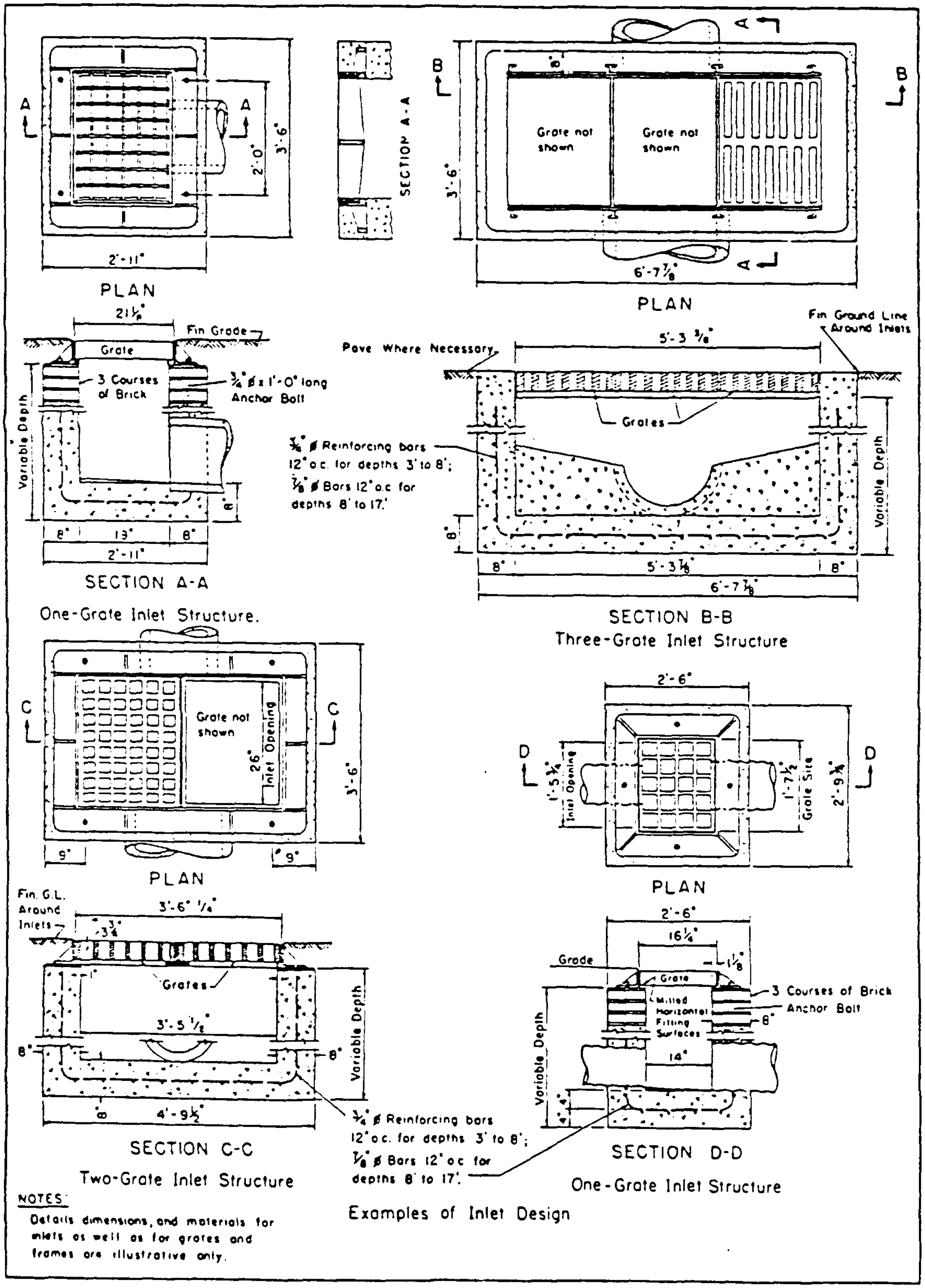


Figure 3.8 Examples of Inlet Design (Ref. 1).

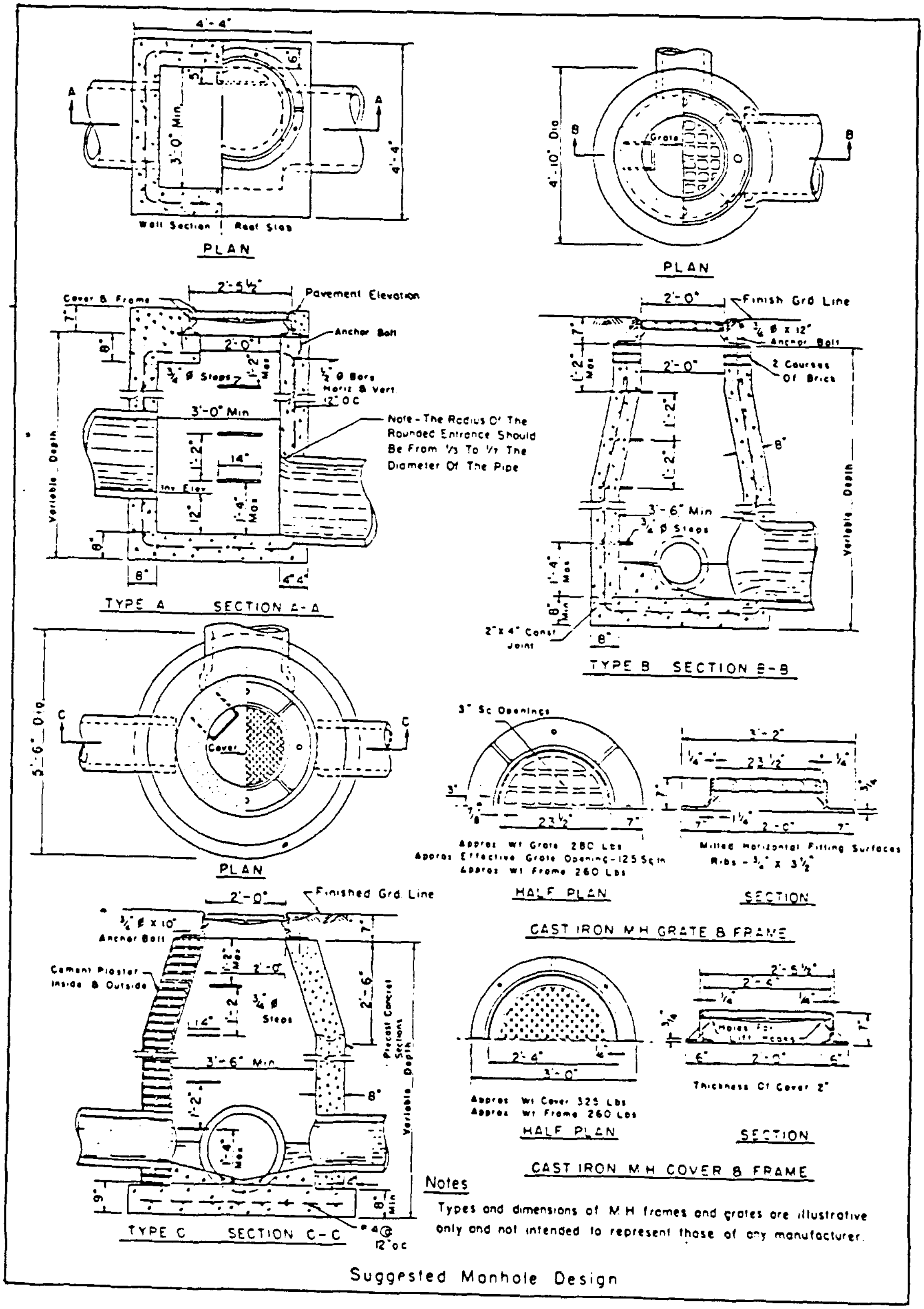


Figure 3.9 Manhole Design Standards (Ref. 1).

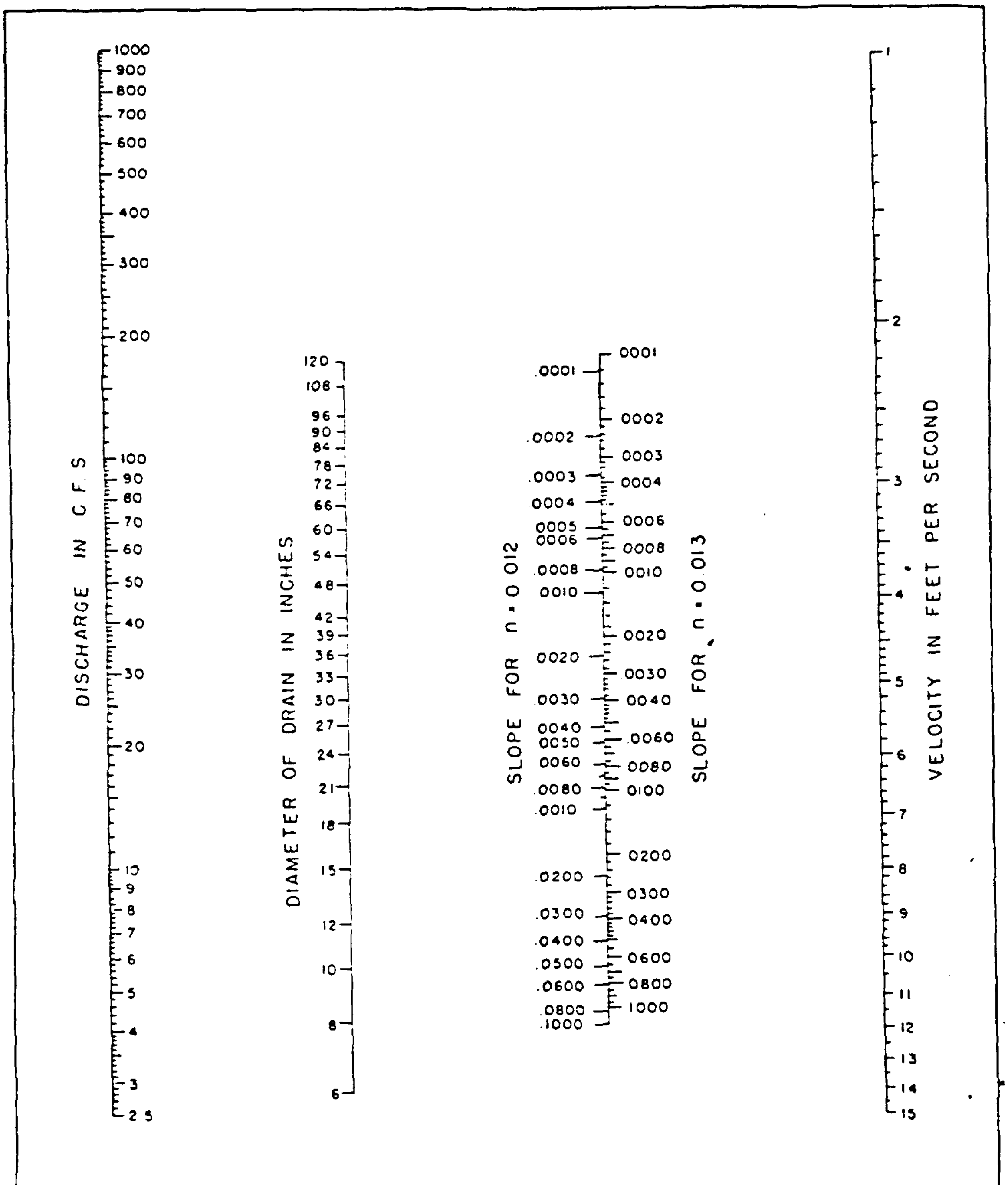
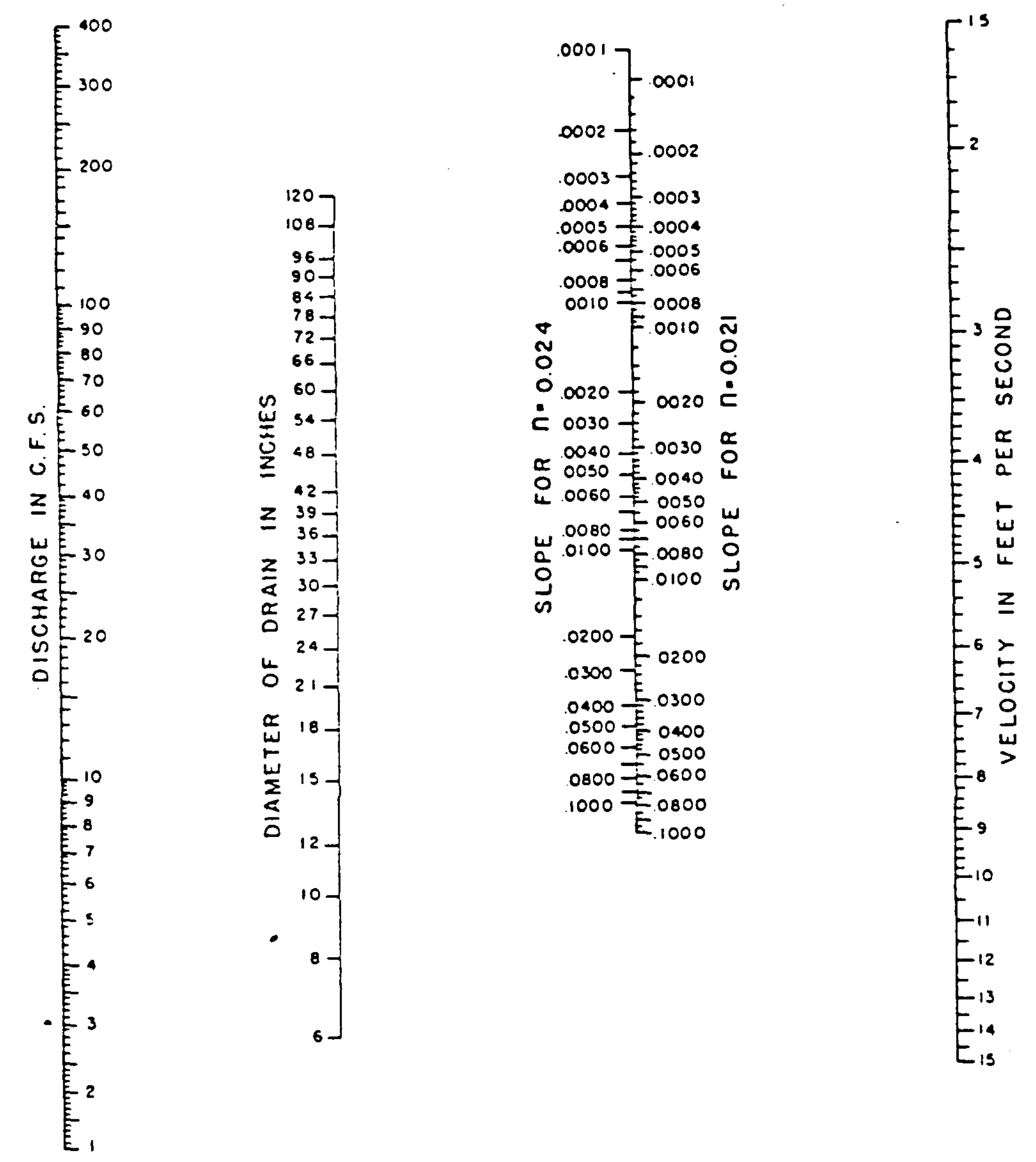


Figure 3.10 Nomograph for Computing Required Circular Pipe Drain Size for n=0.012 or n=0.013 (Ref. 1).



Nomograph for computing required size of circular drain, flowing full - n=0.021 OR 0.024

Figure 3.11 Nomograph for Computing Required Circular Pipe Drain Size for n=0.021 or n=0.024 (Ref. 1).

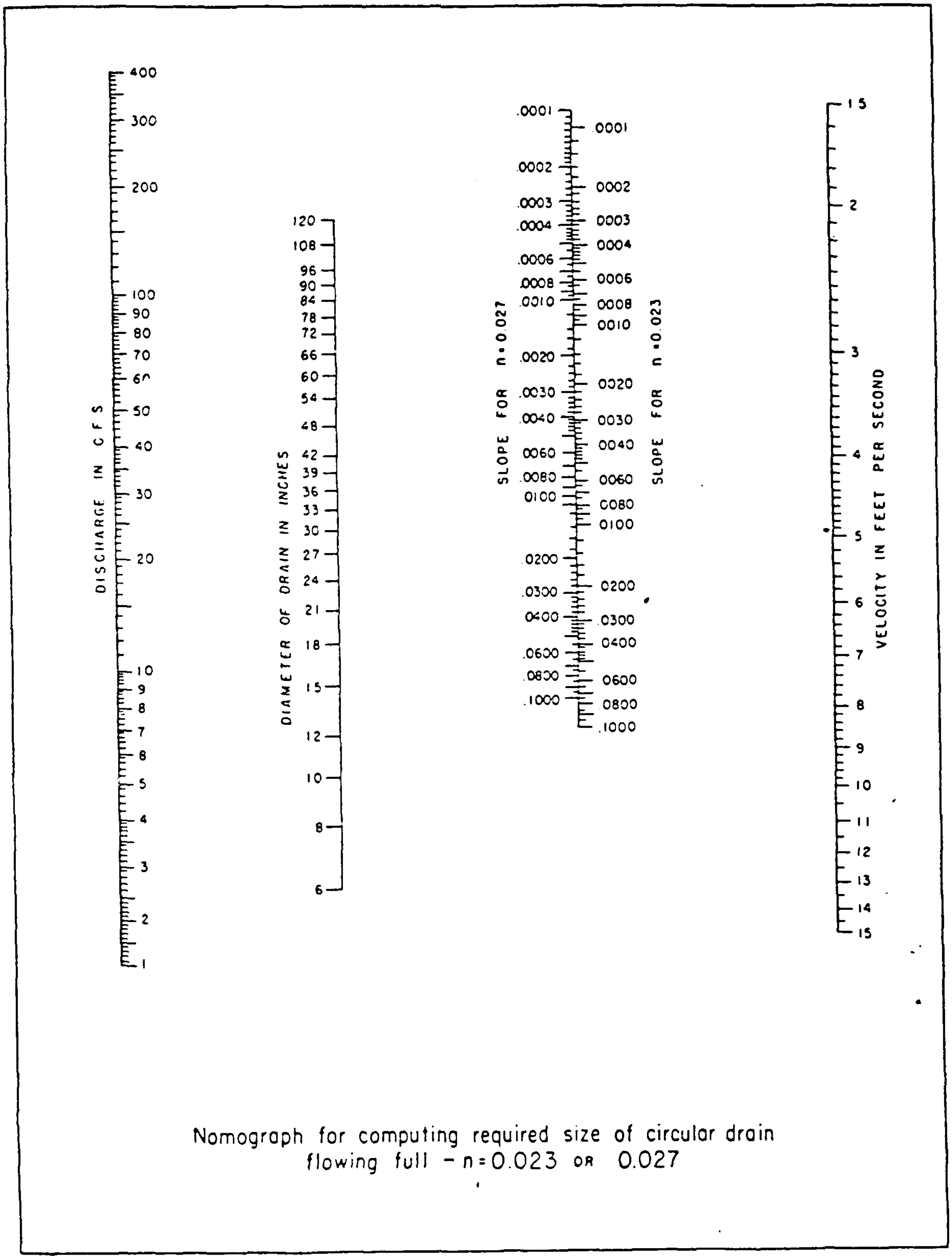


Figure 3.12 Nomograph for Computing Required Circular Pipe Drain Size for n=0.023 or n=0.027 (Ref. 1).

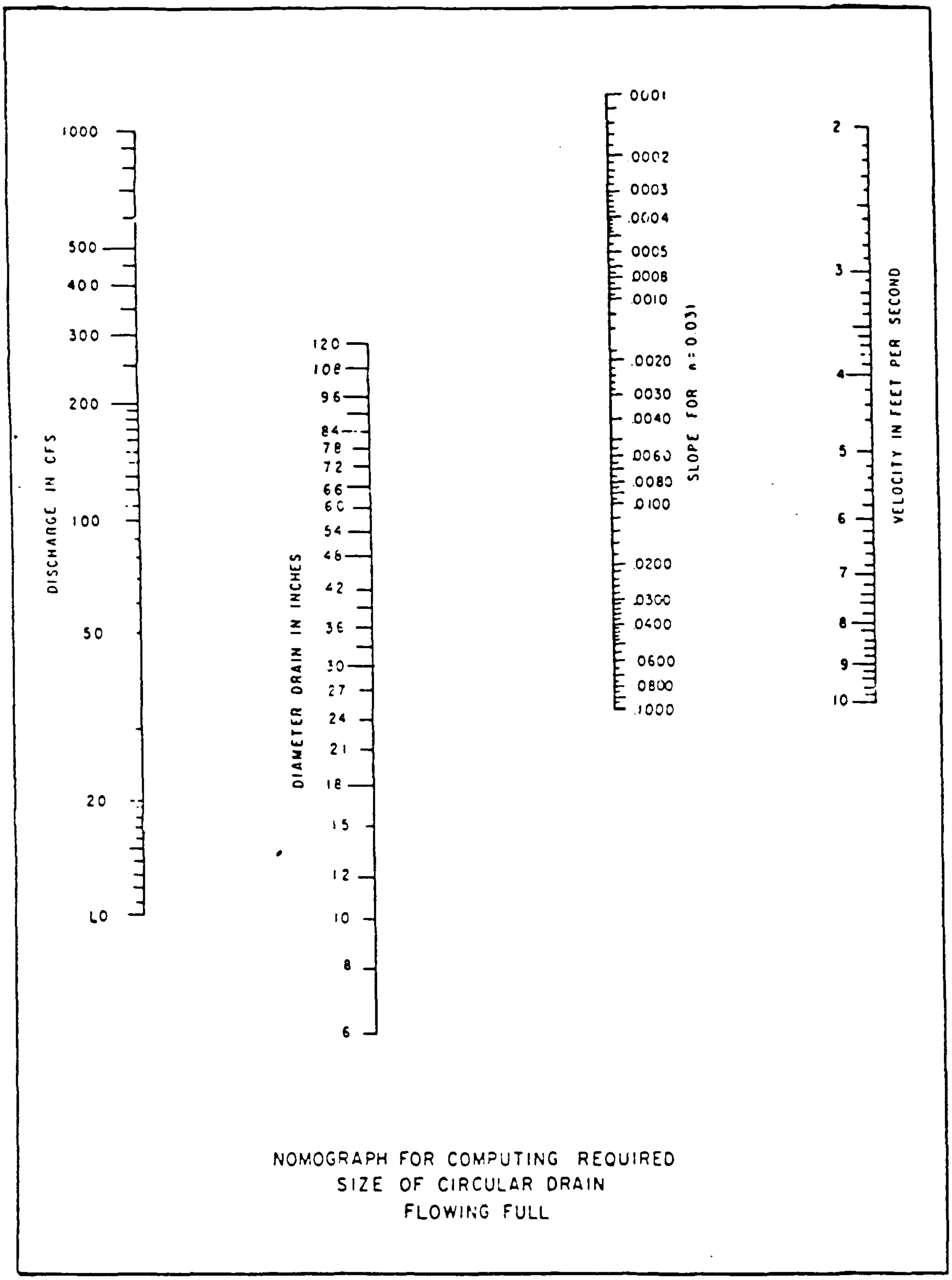


Figure 3.13 Nomograph for Computing Required Size of Full Flowing Circular Pipe Drain for n=0.031 (Ref. 1).

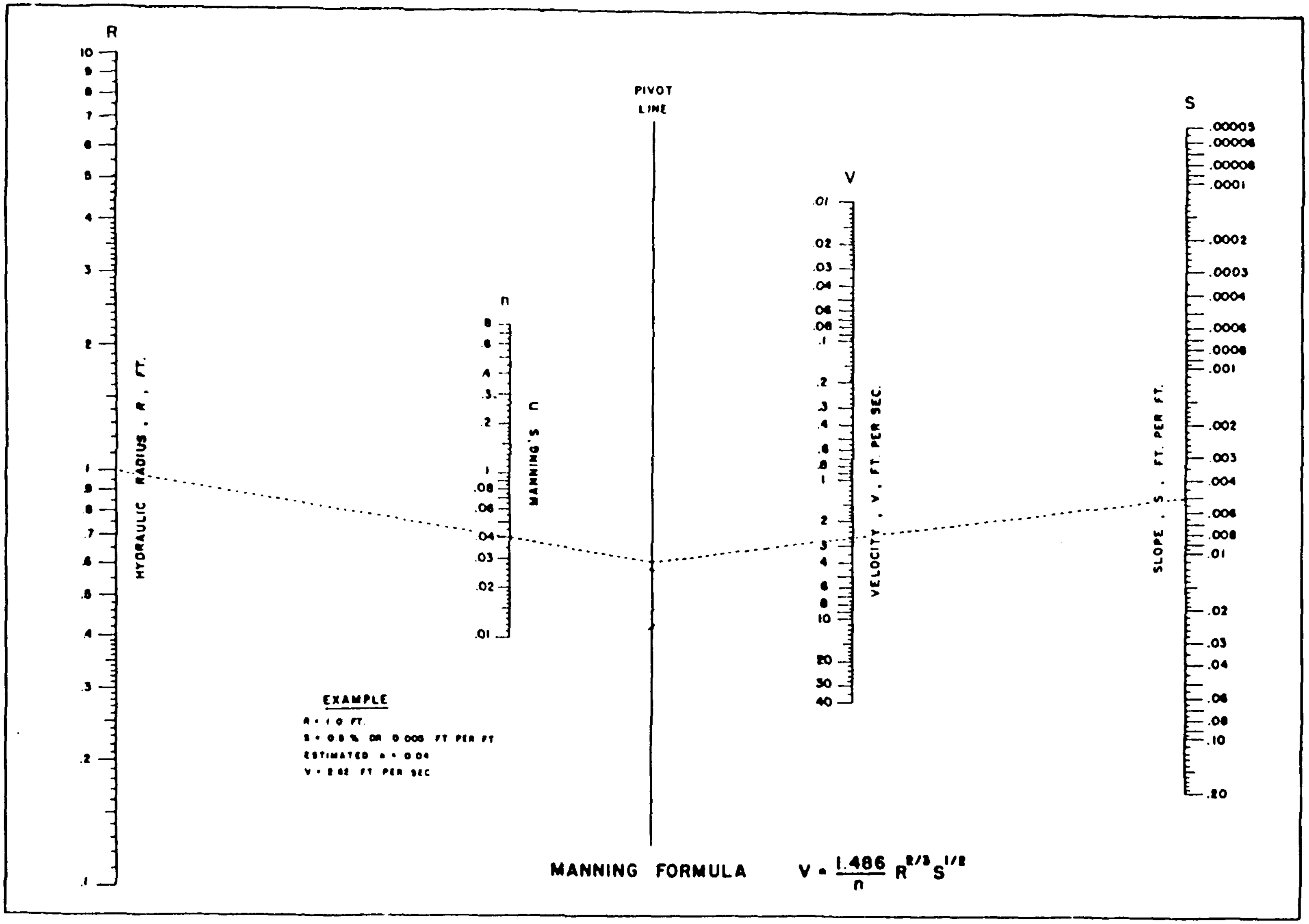


Figure 3.14 Nomograph Solution of the Manning Formula for Open Channels (Ref. 1).

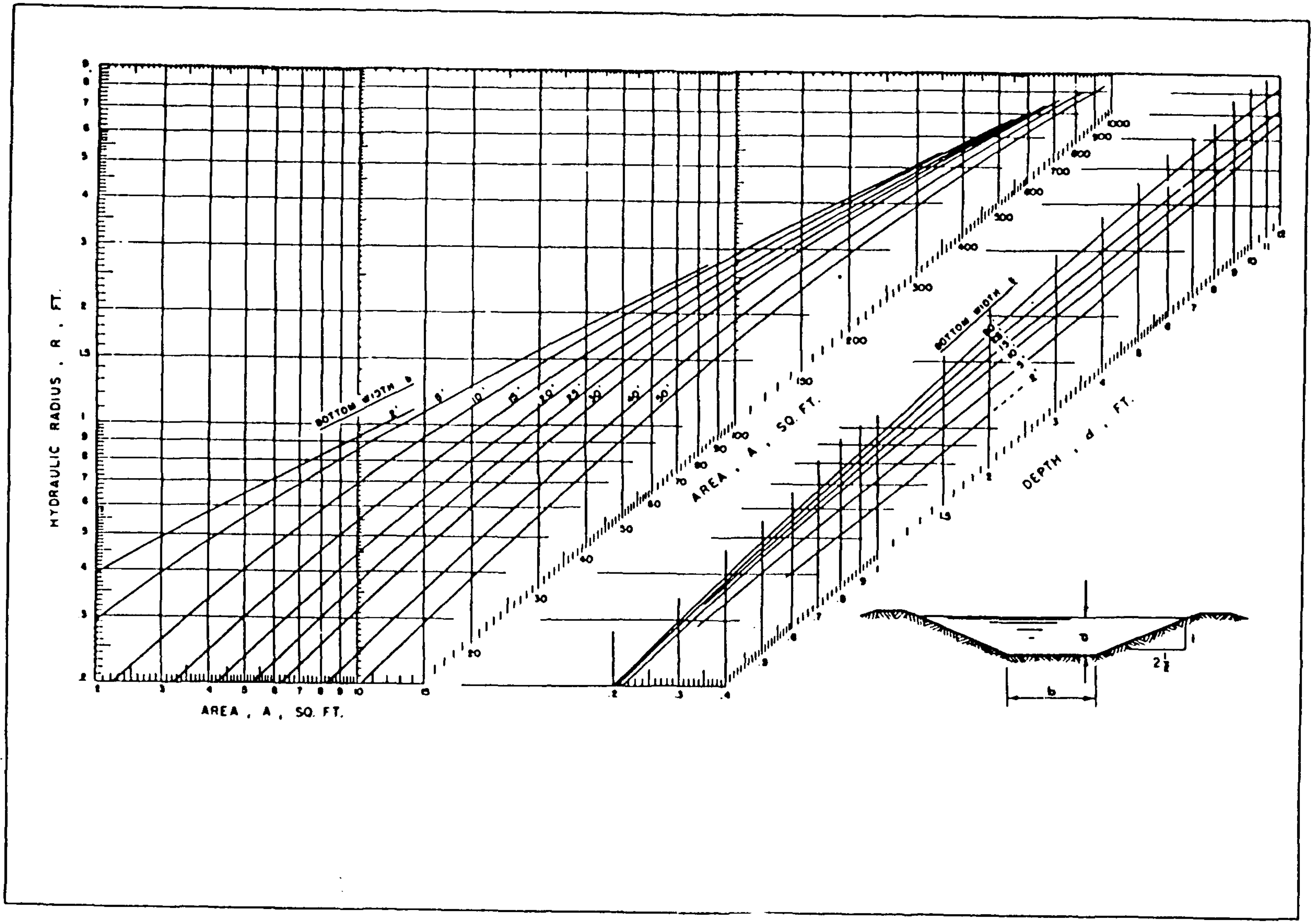


Figure 3.15 Dimensions of Trapezoidal Channels with 2.5 to 1 Side Slope (Ref. 1).

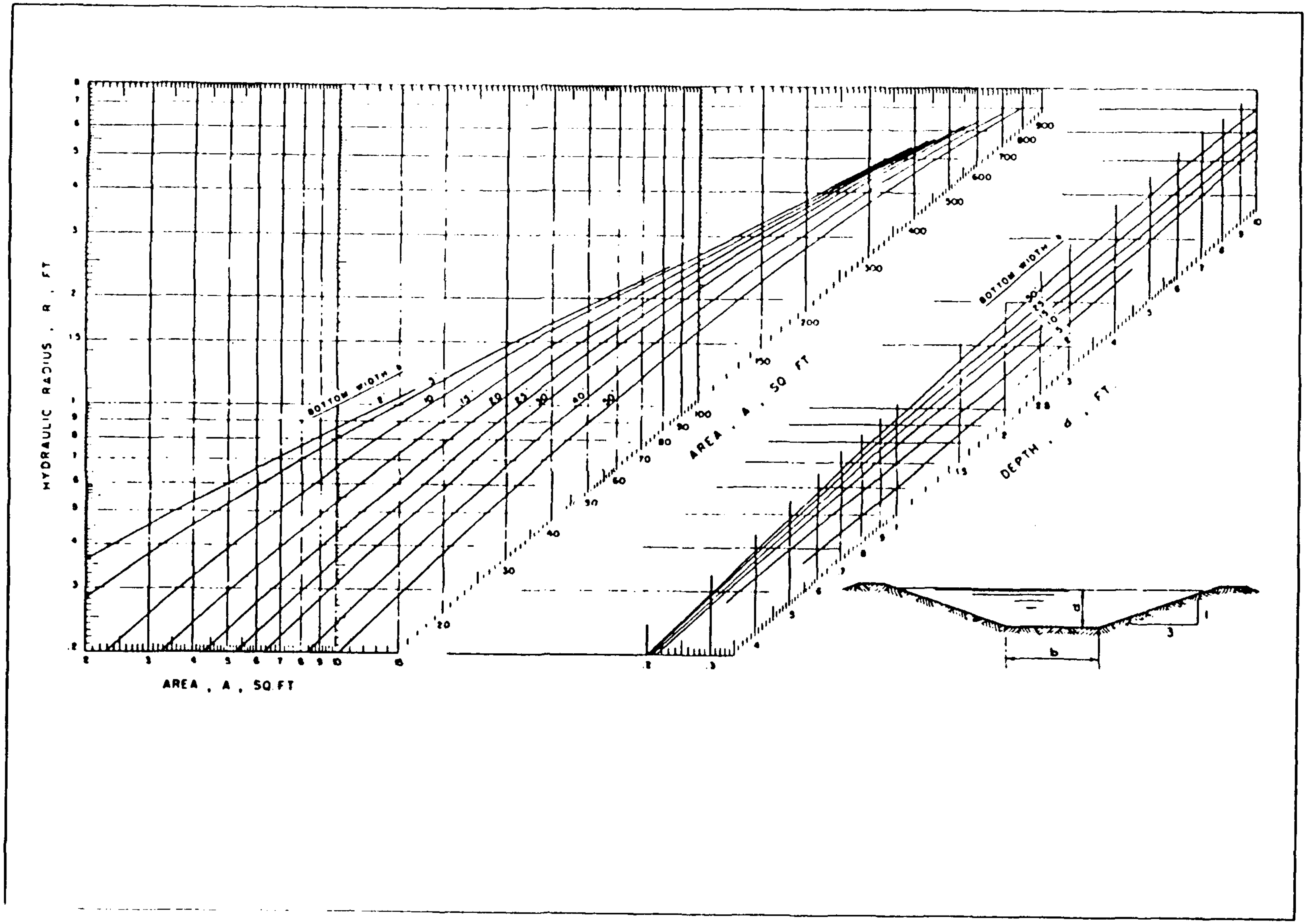


Figure 3.16 Dimensions of Trapezoidal Channels with 3 to 1 Side Slopes (Ref. 1).

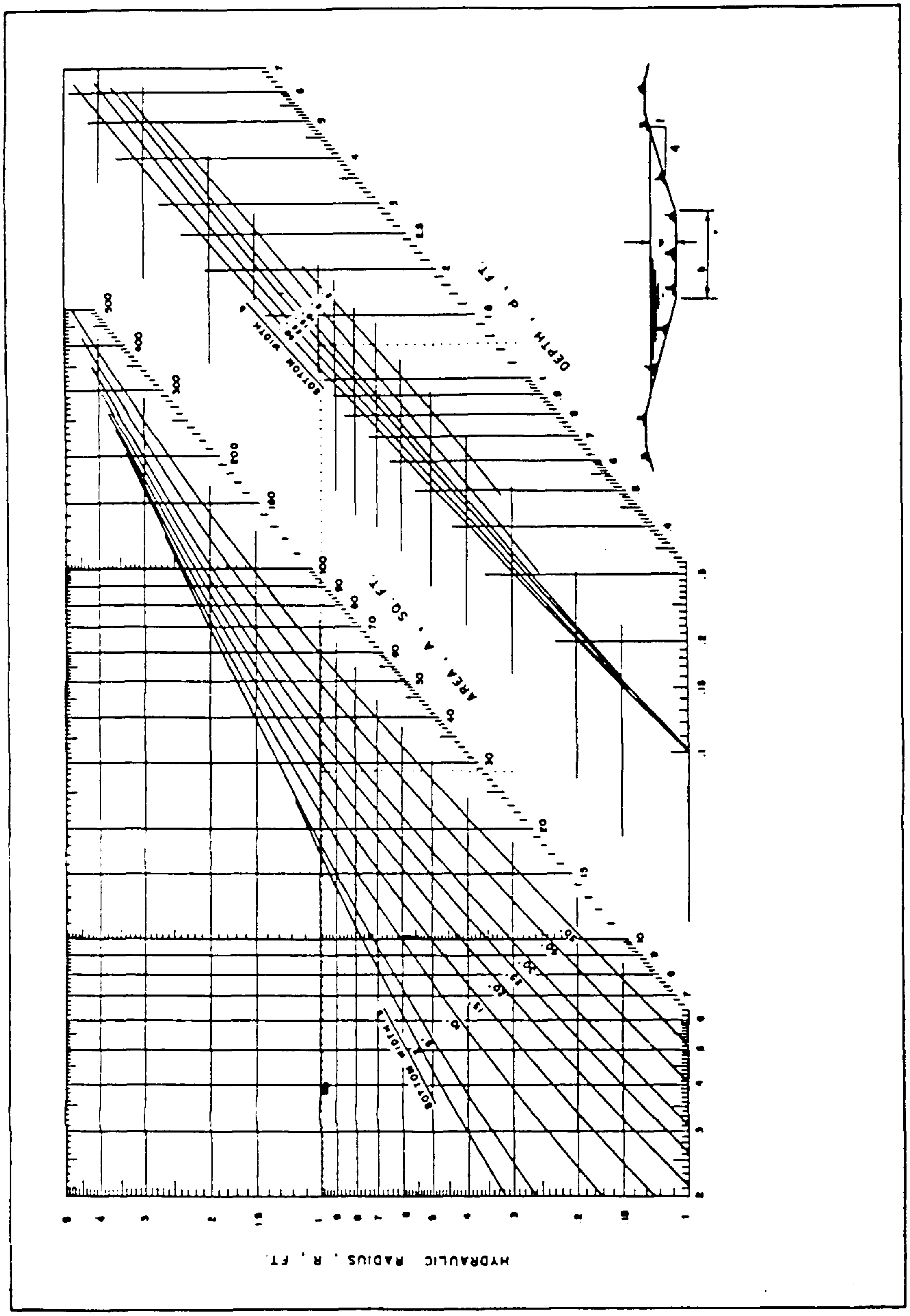


Figure 3.17 Dimensions of Trapizoidal Channels with 4 to 1 Side Slopes (Ref. 1).

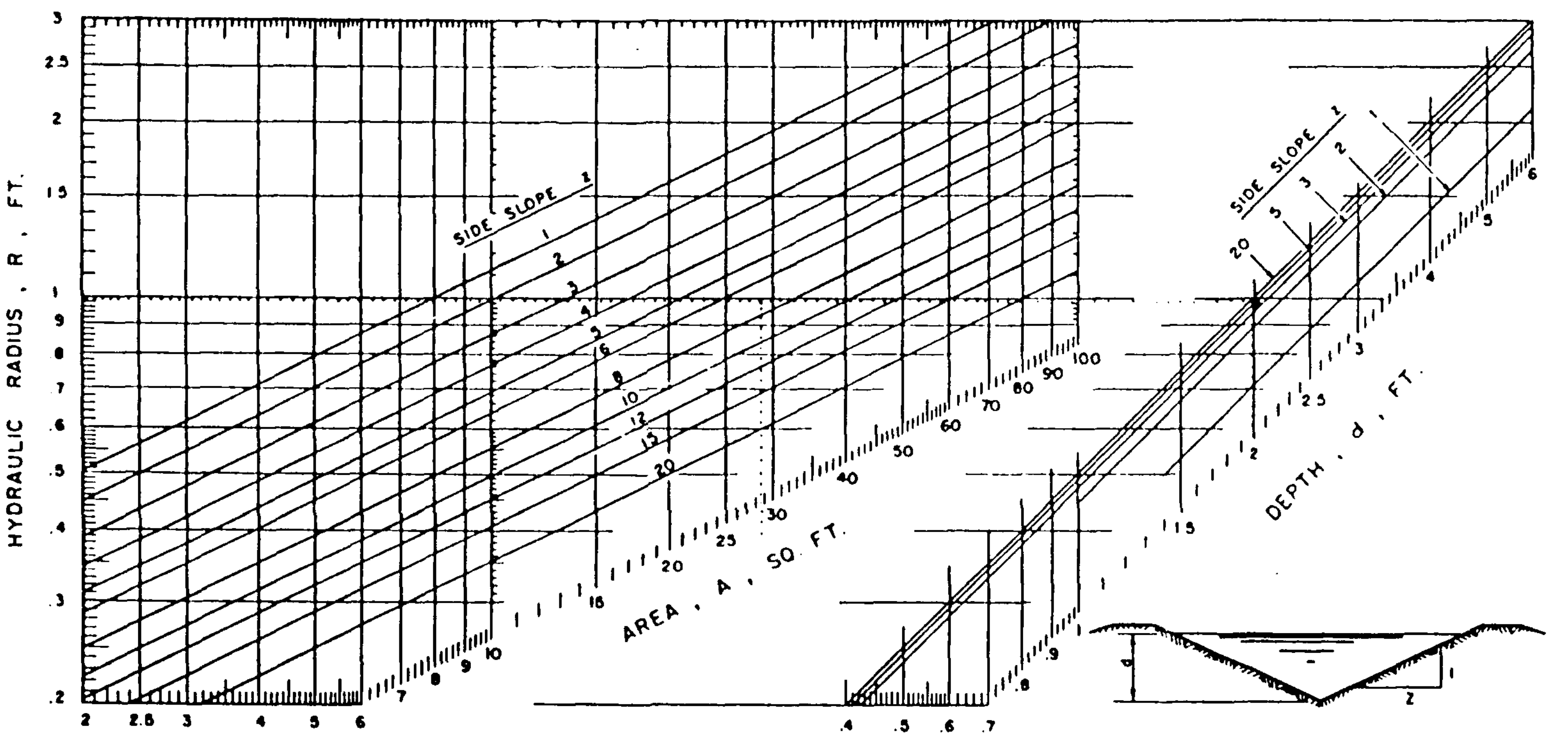
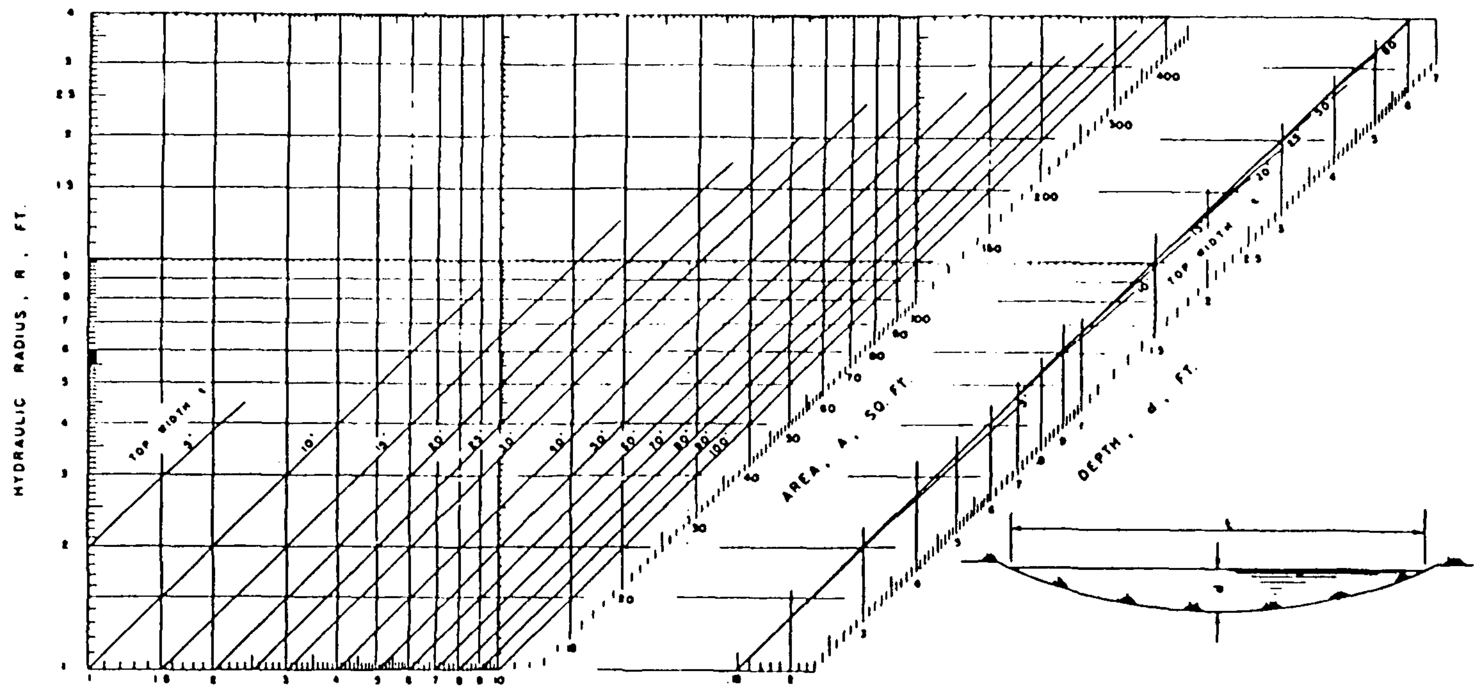


Figure 3.18 Dimensions of Triangular Channels (Ref. 1).



NOTE: THIS CHART TO BE USED IN CONJUNCTION WITH THE NOMOGRAPHIC SOLUTION (FIG. 19)

Figure 3.19 Dimensions for Parabolic Channels (Ref. 1).

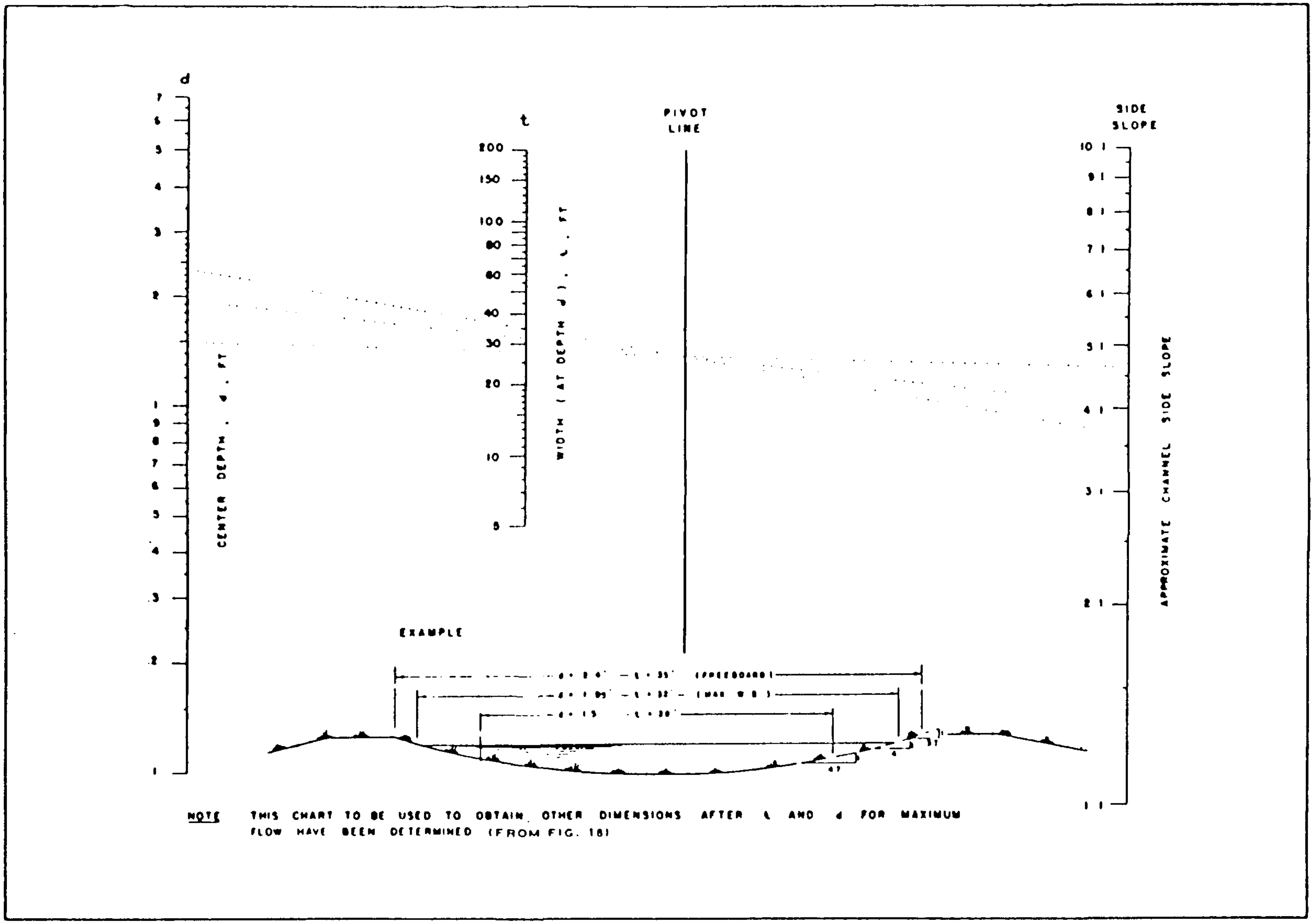
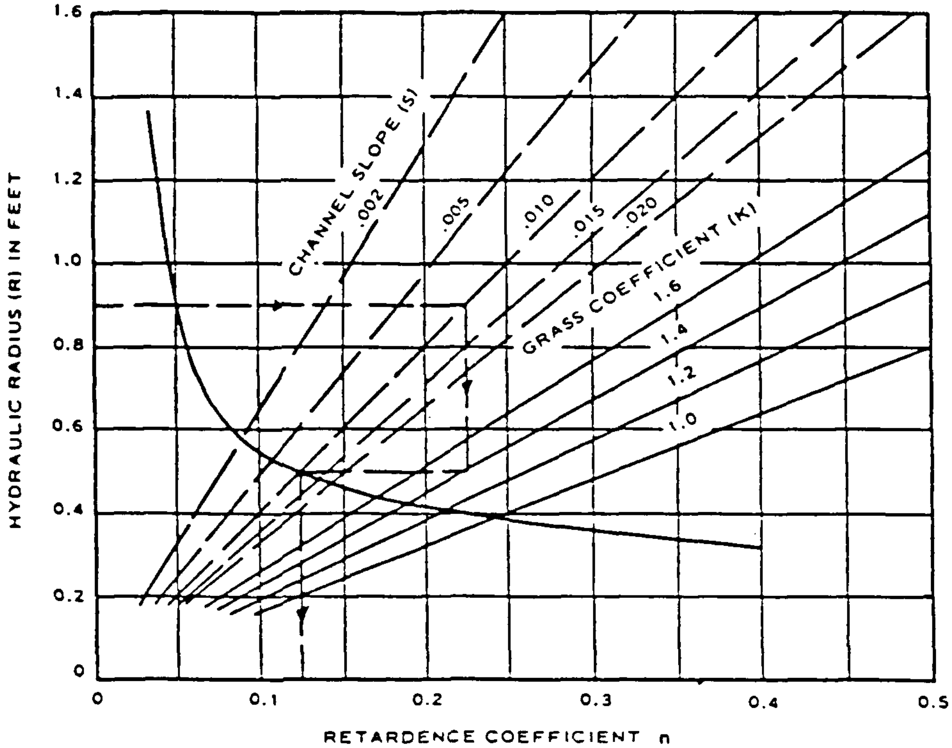


Figure 3.20 Solution for Dimensions of Parabolic Channels (Ref. 1).



GRASS COEFFICIENTS (K) FOR DENSE AIRFIELD TURF

GRASS SPECIES	AVG LENGTH OF GRASS IN INCHES		
	<6	6-12	>12
BUFFALO	1.6	--	--
BLUE GRAMMA	1.5	1.4	1.3
BLUE GRASS	1.4	1.3	1.2
BERMUDA	1.4	1.3	1.2
LESPEDEZA SERICEA	1.3	1.2	1.1

EXAMPLE:

DETERMINE n FOR 4-INCH BERMUDA GRASS CHANNEL WITH R = 0.9 AND S = .010.

FROM TABLE K = 1.4 AND FROM GRAPH, FOLLOWING DASHED LINE, n IS EQUAL TO 0.125.

Figure 3.21 Retardance Coefficients for Flow in Turfed Channels (Ref. 1).

Chapter 4

PAVEMENT SURFACE DRAINAGE

4.1 Introduction

The FAA has conducted numerous studies concerning effects of pavement surface properties on drainage and aircraft performance (1,2). Aircraft performance on wet pavement is greatly influenced by the friction between the tires and the surface. Under certain conditions water accumulation on an airport pavement can cause hydroplaning which will result in loss of aircraft breaking and directional control.

Figure 4.1 shows the factors affecting aircraft performance on wet airport pavements (3). It is generally recognized that both microtexture and macrotecture of the pavement surface influence aircraft performance, Figure 4.2 (3). Pavement microstructure is considered to be related to the finer asperities on the individual aggregate particles. The pavement macrostructure relates to the larger asperities created by the aggregate particles and the surface finishing procedures. It is felt that the engineers will have more control over the macrostructure than microstructure of a pavement surface.

Control of the macrostructure on airport pavement surfaces is best controlled by grooving and use of porous friction surfaces (PFS). These procedures have been found to promote surface drainage and increase aircraft tire friction on the pavement.

4.2 Pavement Surface Grooving

Standiford, Gravel, and Lenke (3) have indicated that saw-cut grooves can be made in both asphalt concrete and portland cement concrete pavements. They indicate that grooves can be made in portland cement concrete by a heavy rake, wire comb, or wire tines while it is still in the plastic state. They indicated that reflex percussive grooves worked well in dense asphalt concrete pavements.

Grooving helps to prevent hydroplaning by providing channels for water to escape from beneath the tire at the tire/pavement interface, thus reducing the chances of hydroplaning. Also the drainage rate is increased by the polished groove channels created by diamond saw cutting which greatly reduces water flow resistance when compared to water draining over the comparatively rough pavement surface.

The three identifying groove dimensions are width, depth, and pitch or distance between groove centerlines. An investigation by Agrawal and Daiutolo (4) concluded that changing the pitch created substantially more savings than changing groove size. The FAA recommends (1/4-in. wide by 1/4-in. deep grooves spaced at 1 1/2 in. for installation on runways where the potential for hydroplaning exists (1). Experiments by Agrawal and Daiutolo (4) were conducted to measure the coefficient of friction under different conditions for speeds from 70- to 150- knots and pitches up to 4 in. The friction levels available on grooves with a 3-in. pitch under wet operating conditions were not significantly below those obtained on grooves spaced at 1 1/2 in. while the cost of installation was reduced by about 25%. Comparisons also showed

that reflex percussive grooves spaced at 4 1/2 in. were comparable to conventional grooves spaced at 2 in. The installation of these grooves could be as low as one half that of conventional grooves with a pitch of 1 1/2 in.

Reed, Kibler, and Agrawal (5) have developed a mathematical model to simulate runoff from grooved runways. A hydraulically equivalent ungrooved surface which has a width equal to the wetted perimeter of a grooved surface is used to preserve the shear area. The model simulates flow depths for different groove spacings. The model parameters used are the transverse slope of the surface, surface texture, groove size and shape, groove spacing, and a uniform rainfall rate.

Grooving can cause damage to large, heavy aircraft tires when landing as they first skid on the runway before rotation is started. The damage, known as chevron cuts, was investigated by NASA (6). Their conclusion was that the damage can be reduced by prerotation of the tires. Also, in the early 1970's, the aircraft tire industry developed new tread rubber compounds and tread designs that significantly reduce the amount of chevron cuts from runway grooves. Data from American Airlines reports, show that this increased the number of landings per tire change by 50% while the number of grooved runways increased approximately three times (6).

Graul and Lenke (7) evaluated the problem of tire rubber build-up on friction for seven grooved portland cement concrete pavements and one grooved dense graded asphalt concrete pavement. They indicated that pavement grooving was essential for obtaining high friction levels in airport pavements. They also indicated that pavement microstructure was difficult to quantify from friction measurements and that improved methods for measuring pavement macrostructure were needed.

Frequent periodic inspections and maintenance of grooved pavements are necessary in order to provide good surface drainage and high values of friction. Tire rubber and other contaminants need to be removed periodically by means of high pressure water jets, chemical treatment, high velocity impact with abrasive materials, and mechanical grinding. Figure 4.3 provides a general guideline for frequency of rubber removal as a function of annual loadings for a range of grooved and textured pavement systems (1).

4.3 Porous Friction Courses

An Open-Graded Asphalt Friction Course or Porous Friction Course (PFC) is a type of surface treatment, usually ranging from 3/4-in. to 1 1/2-in. thick, designed to reduce hydroplaning and increase skid resistance on pavements. This is accomplished by allowing the surface water to drain through the layer, both vertically and horizontally. The major reason for the effectiveness of the PFC is the elimination or reduction in thickness of the sheets of water between the tire and the pavement surface.

Since the PFC is considered to be a surface treatment (less than 1-in. to 1 1/2-in. thick) it doesn't add to the structural integrity of the pavement structure. It is, however, processed in a plant and laid down in a manner similar to a conventional asphalt concrete surface layer as opposed to being sprayed on like most surface treatments.

Two important design parameters for a PFC are the asphalt cement content and the gradation of the aggregate. A change in either one of the two in the design mix can alter the performance of the PFC greatly.

The gradation of the aggregate is very important since the main purpose of a PFC is to retain enough void content to enable adequate drainage of water through the layer. A minimum void content of about 15% is recommended for design purposes. Therefore, the aggregate gradation has to be fairly uniform to provide a high void content. A typical gradation for an aggregate to be used in a PFC is shown in Table 4.1 (8). Other aggregate requirements for a PFC include low abrasion loss, high resistance to polishing, and an aggregate with two or more crushed surfaces. As shown in Table 4.1, there is some fine aggregate in the gradation. This small amount of fines is just enough for stabilization of the coarse fraction which constitutes the majority of the aggregate. One important property of the coarse aggregate fraction is skid resistance. Skid resistance is a function of the microtexture and macrotexture which are predominantly properties supplied by the coarse aggregate.

A second important factor in the design of a PFC is the asphalt content. The PFC does not conform to the usual standards of stability and flow for choosing asphalt cement content. On the basis of these two properties, the PFC does not yield definitive results. Therefore, a substantial amount of engineering judgment is required in the selection of the asphalt cement content in the mix. Too little asphalt cement can cause premature stripping and ravelling to occur whereas too much will fill the void space and hinder drainage. Great care must be taken in selecting the quantity and grade of asphalt cement and optimum mixing temperature used for the PFC. Grades of AC-10, AC-20, AC-40, AR-40, and AR-80 have been recommended for use in the mix, depending on the climate. The more viscous binders will provide for a thicker film on the aggregate and can be mixed at a higher temperature without running off the aggregate.

Some benefits other than improved skid resistance and decreasing hydroplaning can be attributed to the addition of a PFC layer. The PFC retards the formation of ice on the pavement surface. Also, there is improved surface smoothness, improved visibility of painted markings, and less glare at night during wet weather.

The key to the success of the PFC is its permeability. The permeability has to be maintained at an adequate level at all times to ensure a reduction in hydroplaning. This means that maintenance operations should focus on the removal of silt, sand, rubber, and other foreign matter from the wearing course to maintain its high permeability. Graul, Lenke, and Standiford (9) have indicated that rubber removal from PFC pavement is necessary where traffic is heavy. They also indicated that high pressure water removal techniques will not damage a good PFC pavement if the operation is carried out at regular intervals before any foreign materials become lodged in the voids.

4.4 Summary

Airport pavement surface drainage can be enhanced through the use of surface grooves and porous friction courses (PFC). Groove size and spacing are important parameters to be considered when designing a pavement surface

with excellent drainage and friction properties. Porous friction courses (PFC) provide excellent surface drainage properties by means of their high void content. For both grooved pavements and PFC surfaces, periodic maintenance to remove tire rubber and other foreign materials is very important for satisfactory performance.

REFERENCES

1. "Measurement, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces," AC No. 150/5320-12A, Federal Aviation Administration, Washington, D. C., 1986.

2. Hare, J. A., Pur, R. A., and Dempsey, B. J., "Airport Pavement Drainage," Synthesis Report, DOT/FAA/RD-90/24, Federal Aviation Administration, Washington, D. C., 1990.

3. Standiford, D. L., Graul, R. A., and Lenke, L. R., "Permeability Equipment for Porous Friction Surfaces," Interim Report, DOT/FAA/PM-85/31, Federal Aviation Administration, Washington, D.C., 1985.

4. Agrawal, S. K. and Daiutolo, H., "The Braking Performance of an Aircraft Tire on Grooved Portland Cement Concrete Surfaces," Interim Report, FAA-RD-80-78, Federal Aviation Administration Technical Center, Atlantic City Airport, N.J., 1981.

5. Reed, J. R., Kibler, D. F., and Agrawal, S. K., "Mathematical Model of Runoff from Grooved Runways," Transportation Research Circular No. 274, Transportation Research Board, Washington, D. C., 1984.

6. Byrdsong, T. A., McCarty, J. L., and Yager, T. J., "An Investigation of Aircraft Tire Damage Resulting From Touchdown on Grooved Runway Surfaces," NASA-TN-D-6690, 1972.

7. Graul, R. A. and Lenke, L. R., "Runway Rubber Removal Specification Development: Field Evaluation Results and Data Analysis," Interim Report, DOT/FAA/PM-85/32, Federal Aviation Administration, Washington, D.C., 1985.

8. "Bituminous Material and Mix Design," Department of Civil Engineering, University of Illinois, Champaign-Urbana, 1984.

9. Graul, R. A., Lenke, L. R., and Standiford, D. L., "Runway Rubber Removal Specification Development: Final Report," DOT/FAA/PM-85/33, Federal Aviation Administration, Washington, D. C., 1985.

Table 4.1 A Typical Aggregate Gradation for PFC (Ref. 8).

Sieve	Percent Passing
3/8"	100
#4	30-50
#8	5-15
#200	2-5

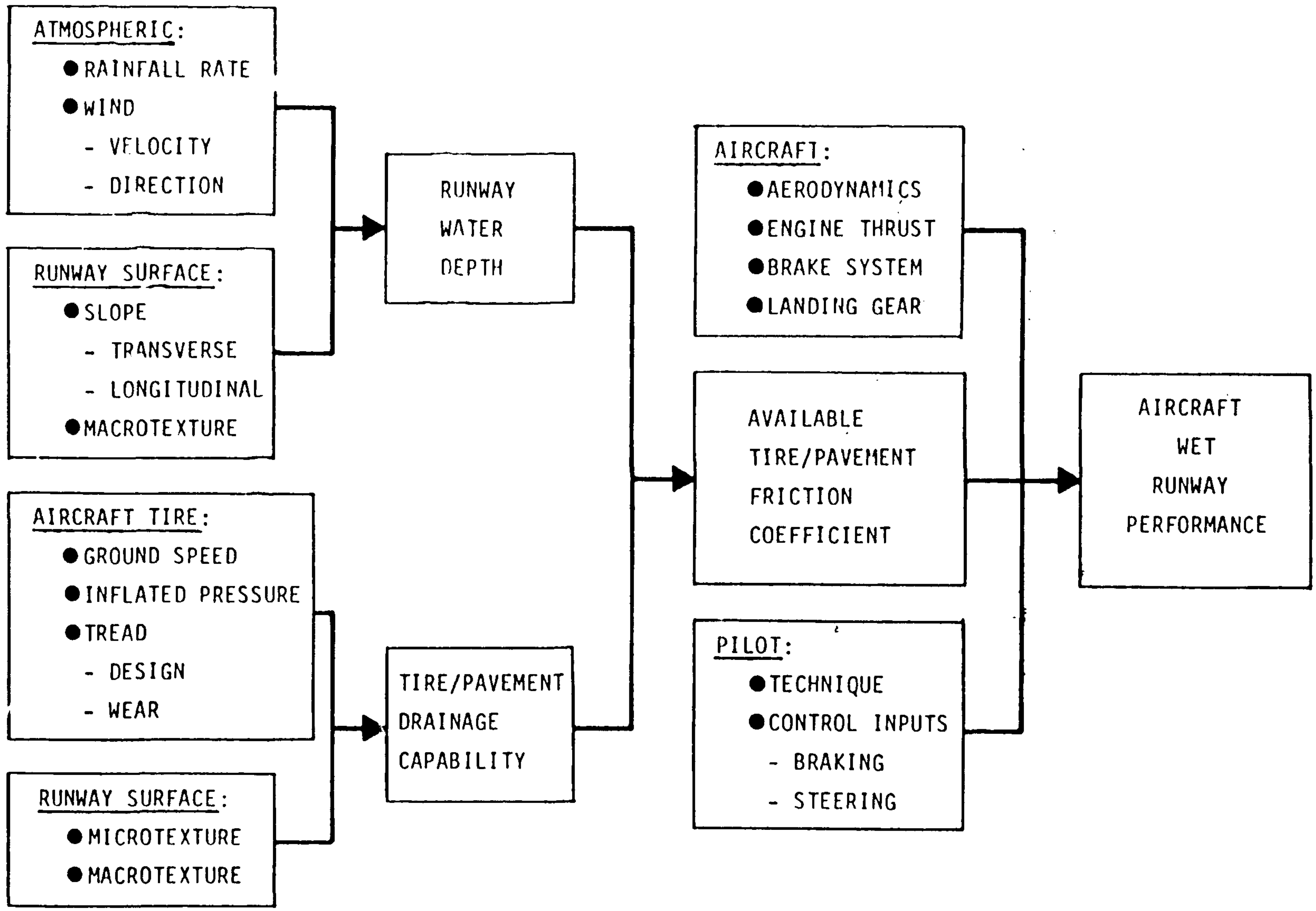


Figure 4.1 Factors Affecting Aircraft Performance on Wet Airport Pavements (Ref. 3).

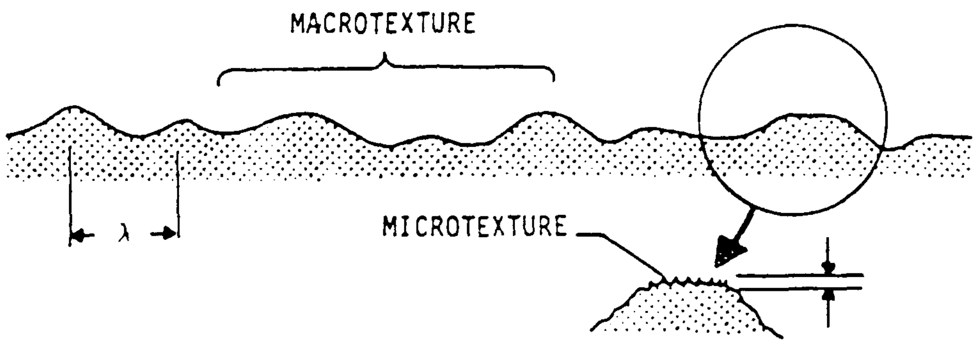


Figure 4.2 Pavement Surface Microtexture and Macrotexture Concepts (Ref. 3).

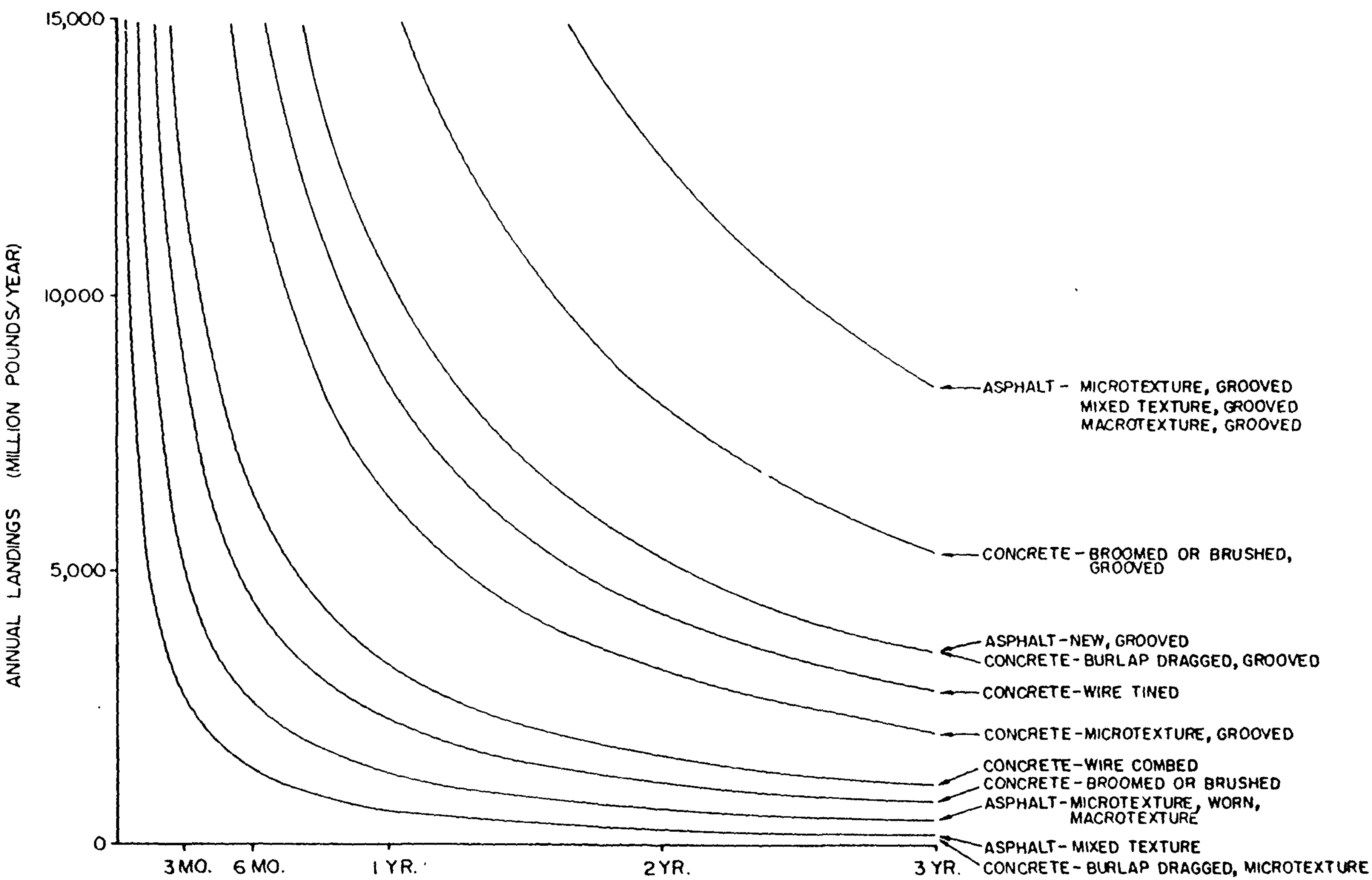


Figure 4.3 Frequency of Rubber Removal as a Function of Annual Landings (Ref. 1).

Chapter 5

PAVEMENT SUBSURFACE DRAINAGE

5.1 Introduction

Properly designed subsurface drainage is a very important consideration in new pavement design as well as in the rehabilitation of existing pavement systems. A thorough understanding of subsurface drainage design and construction is especially important in airport pavements because of the influence large pavement dimensions have on flow hydraulics.

The design of functional subsurface drainage systems for airport pavements require a number of distinct steps as follows:

1. Identify the sources and quantity of water which must be drained from the pavement system.
2. Determine the types of subsurface drainage systems that could be used to remove water from the pavement system.
3. Design the pavement subsurface drainage system in relation to material properties, flow hydraulics, and dimensional variables.
4. Define the procedures and equipment needs for installing the subsurface drainage system.
5. Specify the methods for maintaining and evaluating the subsurface drainage system after construction is completed.

In this chapter procedures for accomplishing steps 1 through 3 will be presented. Steps 4 and 5 will be discussed in later chapters of this report.

5.2 Sources and Quantity of Water in Pavement Systems

5.2.1 General

The sources of water in an airport pavement are similar to those in highway pavements. These sources are shown in Figure 5.1 and can be generalized as follows:

1. Water may seep into the pavement along the edges where the materials are more permeable and where surface and subsurface water often accumulates.
2. Surface water may enter the joints and cracks in the pavement, percolate through the surface, or penetrate at the edges of the pavement surface.
3. The water table can rise as a result of snow melt or rainfall.
4. Water can rise vertically in the capillaries or interconnected water films in the subgrade and pavement materials.
5. Water may move in vapor form through the subgrade and pavement materials depending on temperature gradients and void space.

Moulton (1) has indicated that the water sources can be quantified in terms of surface infiltration, groundwater, melt water from ice lenses, and vertical outflow. The net inflow into the pavement can be determined by summing the values for each water source.

5.2.2 Surface Infiltration

Surface infiltration is often the major source of water that enters the pavement structure. The amount of water infiltrating from the pavement surface is either controlled by the design precipitation rate or the amount of water allowed in by the permeability of the surface course including the joints and cracks. When considering the design precipitation rate, the duration of the rainfall is more important than the intensity (1). The permeability of the surface course is dependent on the water carrying capacity of the cracks or joints, the quantity of cracks or joints, and the area which contributes water flow to each crack or joint (2).

These are several ways in which the surface infiltration rate can be determined. Cedergren (3,4) has suggested that the design infiltration rate be obtained by multiplying the one-hour rainfall with a frequency of occurrence of 1 year, Figure 5.2, with a coefficient between 0.50 and 0.67 for portland cement concrete pavements and between 0.33 and 0.50 for asphalt concrete pavements. In airport drainage a one-hour rainfall with an occurrence frequency of 5 years is recommended.

Ridgeway (5) has proposed equations for estimating water infiltration into both portland cement concrete pavements and asphalt concrete pavements based on crack and joint spacing. Based on Ridgeway's work, Moulton (1) has presented the following equation for determining the design infiltration for portland cement concrete and asphalt concrete pavements:

$$q_i = I_c\left[\frac{N_c}{W} + \frac{W_c}{WC_s}\right] + k_p \qquad \text{(Eq. 5.1)}$$

where:

q_i = the design infiltration rate in cfd/day/ft^2 of pavement subbase,

I_c = crack infiltration rate in cfd/day/ft of crack,

N_c = number of contributing longitudinal cracks,

W = width of the granular subbase subjected to infiltration in ft,

W_c = length of transverse cracks or joints in pavement surface in ft,

C_s = spacing between transverse cracks or joints in ft, and

k_p = infiltration rate through the uncracked pavement surface in cfd/day/ft^2.

In Eq. 5.1 an I_c value of 2.4 cfd/day/ft is recommended for most design applications. The value of C_s is taken as the regular transverse joint spacing in new portland cement concrete pavements and as the anticipated average crack spacing in continuously reinforced and prestressed portland cement concrete pavements or asphalt concrete pavements. A value of C_s of 40 ft is recommended for new asphalt concrete pavements. The value of k_p is

generally quite small for pavement surfaces and it is numerically equal to the coefficient of permeability.

A third alternative for determining infiltration rate is based on work by Dempsey and Robnett (6). Based on measured subdrainage outflows they were able to develop regression equations to relate pavement infiltration to measured precipitation for specific types of pavement surfaces. A typical regression relation for a portland cement concrete highway pavement in Georgia is as follows:

$$PO = 0.48\ PV + 0.32 \qquad \text{(Eq. 5.2)}$$

where:

PO = the pipe outflow volume which can be related to the total amount of water infiltrating the drained pavement surface area in m^3/m^2, and

PV = the precipitation volume in m^3/m^2 of surface area.

A pavement specific type equation similar to Eq. 5.2 could be developed from outflow and precipitation data from an airport pavement.

At the present time it is felt that Eq. 5.1 provides the best estimate of water infiltration into an airport pavement system.

5.2.3 Groundwater

The two sources of groundwater considered in the determination of net inflow rate into a pavement structure are gravity flow or artesian flow. These two water sources should always be considered when designing subsurface drainage systems for highways since they are frequently constructed in hilly terrain where cut slopes are common. Although airport pavements are generally constructed on flat terrain, there are special cases where gravity flow and artesian flow might be considered.

Groundwater flow can be computed by means of hydraulic models, numerical methods or by graphical flow nets. From the flow nets, the total seepage quantities can be estimated from the following equation:

$$q = K_s \Delta H \frac{N_f}{N_d} \qquad \text{(Eq. 5.3)}$$

where:

q = the flux per unit time,

K_s = the saturated hydraulic conductivity or coefficient of permeability,

ΔH = the hydraulic head causing flow, and

$\frac{N_f}{N_d}$ = the shape factor for the flow net where N_f is the number of flow channels and N_d is the number of equipotentials.

From the Highway Subdrainage Design Manual by Moulton (1) the gravity flow can be estimated from Figure 5.3 where the draw-down influence on the watertable can be estimated by the following equation:

$$L_i = 3.8\ (H - H_o) \qquad \text{(Eq. 5.4)}$$

where:

L_i = influence distance in ft, and

$H-H_o$ = draw-down in ft.

From Figure 5.3 the groundwater flow into the pavement subbase is determined from q_2 as follows:

$$q_g = \frac{q_2}{0.5W} \qquad \text{(Eq. 5.5)}$$

where:

q_g = the design inflow rate from gravity in cfd/ft^2,

q_2 = total upward flow into the pavement subbase in cfd/linear ft of pavement, and

W = the width of the pavement subbase layer to be drained in ft.

Artesian flow can be determined for a condition such as that shown in Figure 5.4 by use of Darcy's law in the form:

$$q_a = K_s \frac{\Delta H}{H_o} \qquad \text{(Eq. 5.6)}$$

where:

q_a = artesian inflow in cfd/ft^2 of drainage layer,

ΔH = hydraulic head in ft,

H_o = thickness of layer between artesian aquifer and drainage layer in ft, and

K_s = saturated hydraulic conductivity or coefficient of permeability in ft/day.

5.2.4 Melt Water from Ice Lenses

The formation of ice lenses from frost action is a problem in many pavements. The problem is due to the frost susceptibility of the soil and it is a function of the soil type, availability of groundwater, and the duration and severity of the freezing temperatures. Figure 5.5 shows the maximum

depths of frost penetration in the United States. In a frost susceptible soil moisture will migrate up from the watertable through capillarity and temperature gradients towards the freezing front to initiate or add to the growth of ice lenses, Figure 5.6. Pavement heave with ice lense growth is a major cause of surface roughness during cold weather. A second major problem relates to high water content in the pavement structural section when the ice lenses melt.

The rate of water seepage with ice lense melt depends on the rate of thawing, the permeability of the thawed soil, the stresses caused by the pavement structure and the traffic, and the performance of the drainage system if present. A chart for estimating the design inflow rate of melt water from ice lenses is shown in Figure 5.7. In order to use Figure 5.7 either the average rate of heave or the frost susceptibility classification of the soil must be known. Table 5.1 shows work by Moulton (1) which relates heave rate and frost susceptibility classification to soil type. Figure 5.8 shows a procedure for estimating soil frost susceptibility which was developed by the Corps of Engineers (7). It would also be possible to determine the average rate of heave in the pavement system through use of the Integrated Climatic Model which was discussed in Chapter 2 (8).

In Figure 5.7, σ_p is the vertical subgrade stress caused by the pavement structure. The quantity of melt water, q_m, in Figure 5.7 is determined in terms of cfd/ft^2 of pavement. The saturated hydraulic conductivity of the unfrozen subgrade is represented by K in Figure 5.7.

5.2.5 Vertical Outflow

Some of the water that may infiltrate or accumulate in a pavement structural section could seep vertically out of the pavement layers through the underlying soil strata. Since this vertical seepage tends to decrease the amount of water that must be carried by the pavement drainage system, it should be given very careful consideration.

There are a wide variety of subsurface conditions under which vertical seepage may take place. These can be placed into three broad general categories: (1) the flow is directed toward a watertable, either horizontal or sloping, existing at some depth below the pavement section, Figure 5.9, (2) the subgrade soil or embankment is underlain at some depth by a stratum with a permeability that is very high relative to that of the subgrade or embankment material, thus promoting very nearly vertical flow, Figure 5.10, or (3) the flow is directed vertically and laterally through the underlying embankment and its foundation to exit through a surface of seepage on the embankment slope and/or through the foundation, Figure 5.11.

The outflow of water through the pavement subgrade can be estimated by use of Eq. 5.3 or by graphical relationships shown in Figures 5.9, 5.10, and 5.11 (1). It is generally found that the vertical outflow which is defined as q_v in Figures 5.9, 5.10, and 5.11 and has the units of cfd/ft^2 will be small for fine grained soils of low permeability.

5.2.6 Net Inflow

The net inflow of all water into the structural pavement section should include inflow from all possible sources with some allowance for any vertical outflow which might occur. The net inflow will include some combination of surface infiltration, groundwater from gravity flow or artesian flow, melt water from thawing ice lenses, and vertical outflow. In considering all important possible combinations of inflows and outflows, Moulton (1) has specified the following set of relationships for computing the net inflow, q_n;

$$q_n = q_i \qquad \text{(Eq. 5.7)}$$

$$q_n = q_i + q_g \qquad \text{(Eq. 5.8)}$$

$$q_n = q_i + q_a \qquad \text{(Eq. 5.9)}$$

$$q_n = q_i + q_m \qquad \text{(Eq. 5.10)}$$

$$q_n = q_i - q_v \qquad \text{(Eq. 5.11)}$$

where:

q_n = net inflow,

q_i = inflow from pavement surface infiltration,

q_g = groundwater flow from gravity,

q_a = groundwater flow from artesian conditions,

q_m = inflow from thawing of ice lenses, and

q_v = vertical outflow.

Moulton (1) has indicated infiltration flow should be common to all of the other flow sources as shown in Eq. 5.7 through Eq. 5.11. He has indicated that flow from ice melt water and groundwater are unlikely to occur at the same time since frozen fine grained soils are nearly impermeable. Moulton (1) also indicates that vertical outflow will not occur during groundwater flow from gravity or artesian conditions. Therefore the main objective for determining the net inflow rate for subsurface drainage design should be based on that combination of Eq. 5.7 through Eq. 5.11 which best accounts for all of the water sources and which gives the maximum inflow value.

5.3 Pavement Subsurface Drainage Function

5.3.1 General

Once the design net inflow of water has been determined for a pavement system, the development procedures for removing the water are necessary. Rapid drainage of water from the structural section of airport pavements is especially important because of wide pavement widths which may range up to 200 ft. for runways and considerably greater for aprons. In cold climates

pavement subsurface drainage may become even more important since freeze-thaw problems and frost heave easily occur when water is readily available.

A pavement subsurface drainage system can be classified in several ways based on the source of the subsurface water to be controlled, the function it performs, and its location and geometry. In most pavement work subdrainage is classified in terms of the function performed and, more commonly, in terms of its location and geometry.

5.3.2 Subsurface Drainage Based on Function

In terms of function, a subsurface drainage system would be required to accomplish the following:

1. Intercept or cut off the seepage above an impervious boundary.
2. Draw down or lower the water table.
3. Collect the flow from other drainage systems.

Although a subsurface drainage system may be designed to serve only one function, it will often times serve several functions.

5.3.3 Subsurface Drainage Based on Location and Geometry

The most common method of classifying subsurface drainage in pavement systems is based on location and geometry (1). It should be noted that based on location and geometry, the subsurface drainage system controls the source of water as well as satisfies the functional requirements of drainage. A brief definition of subsurface drainage classified by location and geometry is given as follows:

1. <u>Longitudinal Drains</u>: A longitudinal drain is located essentially parallel to the pavement centerline both in horizontal and vertical alignment. It may involve a trench of substantial depth, a collector pipe, and a protective filter. Figure 5.12 shows typical longitudinal drainage systems.

2. <u>Transverse Drains</u>: Subsurface drains that run laterally beneath the pavement or are drilled into the cut slopes are classified as transverse drains. These drains are usually located at right angles to the pavement centerline, although in some cases they may be skewed. Transverse drains can be especially important at the sag of a vertical curve. Figure 5.13 shows a transverse drainage system.

3. <u>Drainage Blanket</u>: The term drainage blanket is applied to a very permeable layer whose width and length are large relative to its thickness. The horizontal drainage blanket can be used beneath or as an integral part of the pavement structure to remove water from infiltration or to remove groundwater from gravity or artesian sources. A typical drainage blanket is shown in Figure 5.14. These materials may require specially graded aggregate layers to serve as filters to prevent clogging and erosion problems.

4. <u>Well Systems</u>: Systems of vertical wells are sometimes used to control the flow of groundwater and relieve porewater pressures in potentially troublesome subgrades. In this application, they may be pumped for temporary lowering of the water table during construction or left to overflow for the

relief of artesian pressures. Sand-filled vertical wells or wick drains can be used to accelerate drainage of soft compressible foundation materials which are undergoing consolidation. Figure 5.15 shows a vertical well system.

During construction and maintenance operations on airport pavements, several different types of subsurface drainage systems may be required. For this reason considerable care is recommended when designing the more elaborate and complex systems.

5.4 Pavement Subsurface Drainage System Design Guidelines

5.4.1 General

This section will describe the procedures for designing the important components of a pavement subsurface drainage system. The design procedures are presented primarily for drainage of the pavement structural section and shallow water sources.

Under ideal conditions a pavement subsurface drainage system has at least five essential components as follows:

1. A subbase layer or drainage blanket layer with a high saturated coefficient of permeability or hydraulic conductivity.
2. A filter layer of granular material or geotextile between the subgrade and permeable subbase layer.
3. A longitudinal pavement edge drain as well as transverse drains and other drains as needed.
4. Outlet pipe to carry water from the pavement to a storm drain or surface ditch.
5. Headwalls and outlet markers to protect outlet pipes from damage.

These five components need to be properly integrated to ensure a continuity of water flow through the subdrainage system as shown by the water flow along path A-B-C-D-E-F in Figure 5.16. The water first enters the pavement structure at A (a joint or crack, where most of the excess water in the base course originates) and flows to B, the surface course-base course interface. It then flows to C, an interior point in the subbase drainage layer and on to D, the longitudinal edge drain. The water then flows to E, the entrance to the outlet pipe, and from there to F, where the water is properly disposed. There are basically five segments of flow in drainage of a structural pavement system which can be defined as A-B, B-C, C-D, D-E, and E-F. Along the flow path each segment should have an equivalent or higher discharge capacity than the preceding segment. This will prevent any restrictions that might occur in the drainage system. For example, segment E-F the outlet pipe should have an equivalent or higher discharge capacity than segment D-E, the longitudinal edge drain. The following sections contain descriptions of and design procedures for the components in a subsurface drainage system.

5.4.2 Pavement Subbase or Drainage Blanket Layer Design

The first essential component of a pavement subsurface drainage system is the subbase layer or drainage blanket layer. This layer is generally considered to be a structural component of the pavement system. The outflow

capabilities of the drainage layer are very important and the aggregate used in the layer should have a high coefficient of permeability to remove any water which has found its way into the pavement structure.

Figure 5.17 shows the effect of grain-size distribution on the permeability of granular materials. It can be generally noted that the permeability is substantially dependent upon the percentages of fine materials below the No. 4 sieve. In highway pavement systems a minimum saturated permeability coefficient of 1000 ft/day is recommended for an open graded drainage blanket. Aggregate gradation sizes from 1 in. to No. 4 sieve, 3/4 in. to No. 4 sieve, and 3/8 in. to No. 4 sieve can easily exceed the 1000 ft/day permeability coefficient value and extend up to saturated permeability coefficients which exceed 20,000 ft/day. Table 5.2 provides two aggregate gradations which have been found to provide very good drainage in highway and airport pavements in Illinois. Table 5.3 shows open graded aggregate gradations used by New Jersey DOT and Pennsylvania DOT for drainable subbases.

The drainage layer flow requirements can be determined by application of Darcy's equation or from work by Moulton (1). From knowledge of the net inflow of water into the pavement, Moulton (1) has provided a procedure to determine the depth of flow in a granular subbase layer, H_m, based on the saturated permeability coefficient, K_d, length of flow path, L, and the slope of the flow path, S. Figure 5.18 shows the relationship for determining the flow depth H_m which is then compared with the actual depth of the subbase drainage layer. The main objective is to ensure that the subbase drainage layer thickness exceeds the flow depth, H_m, required. In some cases where the subbase drainage layer thickness is the controlling parameter the quantity of flow can be increased by using a more permeable material.

The saturated permeability coefficient can be determined from in-situ measurements, laboratory testing, theoretical analysis, and empirical methods (1). Moulton (1) has provided a procedure shown in Figure 5.19 which can be used to estimate the saturated permeability coefficient of granular materials based on the percentage of material passing the No. 200 sieve, effective grain size, and dry density.

When using Figure 5.18 both the length of the water flow path, L, and slope of the flow path, S, will be a function of the longitudinal grade and transverse slope of the airport pavement. These values can be obtained from the following relationships:

$$L = W \sqrt{1 + (g/S_c)^2} \qquad \text{(Eq. 5.12)}$$

where:

L = the length of flow path,

W = width of drainage layer,

g = the longitudinal grade, and

S_c = the transverse slope.

$$S \sqrt{S_c^2 + g_1^2} \qquad \text{(Eq. 5.13)}$$

where:

S = slope of the flow path.

The drainage time for a subbase drainage layer is important from the standpoint of strength and frost problems. Figure 5.20 indicates the generally accepted criteria that aggregate subbases should be maintained at saturation levels below 85%. From previous work by Carpenter, Darter, and Dempsey (9) it is felt that acceptable drainage occurs when a material becomes less than 85% saturated in less than 5 hours, marginal drainage occurs between 5 hours and 10 hours, and unacceptable drainage occurs when the drainage time is greater than 10 hours. This relationship is shown in Figure 2.3 in Chapter 2 of this report.

Procedures for determining the drainage time for pavement subbase materials have been described by Carpenter, Darter, and Dempsey (9). The degree of saturation of the subbase layer can be related to the degree of drainage by the following equation:

$$Sa = 1 - (P.D)U \qquad \text{(Eq. 5.14)}$$

where:

Sa = degree of subbase saturation allowed,

P.D = a percentage index indicating the amount of water in the subbase which can be drained, and

U = the degree of drainage.

The percentage index P.D is determined from the amount of free water which can be drained from subbase layers containing various types and amounts of fine materials, Table 5.4. By knowing the value of P.D from Table 5.4 and the degree of saturation, Sa, the degree of drainage, U, can be determined. From the degree of drainage, U, the time required to reach a specified degree of saturation in the subbase layer can be determined from the time factor obtained in Figure 5.21 (10). This time should be compared with that shown in Figure 2.3 for various levels of acceptability.

The main problem with open graded subbases is that, although they provide excellent drainage, they can be unstable during the construction phase. This problem can be easily solved by stabilizing the open graded aggregate with asphalt cement or portland cement.

Portland cement stabilization has been shown to be effective at application rates in excess of 7% of cement by weight of aggregate. Asphalt cement stabilization has been shown to be effective at application rates of approximately 2.5% by weight of aggregate. The choice of stabilizing agent must be made based on economic and climatic considerations. When using portland cement stabilization, the materials must be adequately compacted immediately after placement and properly cured for a period of at least three days. Adequate compaction has been obtained in the field through the use of static steel wheel rollers and through the use of vibrating screeds mounted on the paving apparatus. Field curing is best achieved through the use of

polyethylene sheeting placed directly over the base materials after placement. When using asphalt cement stabilizing agents, the in-place materials must be compacted using static steel wheel rollers while the mat temperature ranges from 150°F to 250°F depending on the type of compaction equipment utilized. Regardless of stabilizing agent employed, care must be exercised to prevent contamination of the treated base materials which would restrict the permeability of the layer. Open graded aggregate subbases stabilized with portland cement and asphalt cement have been found to provide saturated permeability coefficients in the range of 6,000 ft/day to 18,000 ft/day based on work at the University of Illinois (11). Experienced contractors have also placed unstabilized open graded subbases without major difficulty.

5.4.3 Filter Layers

Filter layers are used to prevent the loss of permeability in drainage layers as a result clogging by fine soil particles. If fine soil is allowed to enter the drainage layer the permeability of the drainage layer and the water removing capability will be substantially decreased. Often, the gradation of drainage layer materials do not satisfy certain filter criteria required to keep fines out of the layer. In order to prevent the infiltration of fines from the subgrade, filters are placed between the drainage layer and the underlying soil. The two types of filters used in subsurface drainage are granular materials and geotextiles.

Granular filters consist of materials with the proper gradation to keep fine soil in the subgrade from working into the drainage layer. The granular soil in the filter layer must satisfy numerous gradation criteria which have been developed to satisfy performance requirements. Moulton (1) has recommended a detailed set of filter criteria as follows:

$$(D_{15})_{filter} \leq 5(D_{85})_{protected\ soil} \qquad \text{(Eq. 5.15)}$$

$$(D_{15})_{filter} \geq 5(D_{15})_{protected\ soil} \qquad \text{(Eq. 5.16)}$$

$$(D_{50})_{filter} \leq 25(D_{50})_{protected\ soil} \qquad \text{(Eq. 5.17)}$$

$$(D_5)_{filter} > 0.074\ \text{mm} \qquad \text{(Eq. 5.18)}$$

$$(C_u)_{filter} = (D_{60})_{filter}/(D_{10})_{filter} \leq 20 \qquad \text{(Eq. 5.19)}$$

Filter criteria should be checked between both the filter and drainage layer and filter and subgrade soil.

Recently geotextiles have found widespread use in filter applications. Koerner (12) has listed several different filter criteria for geotextiles based on either AOS (Apparent Opening Size based on sieve number) or O_{95} (95% opening size). These criteria are listed from the least conservative to the most conservative in Table 5.5. It is generally felt that nonwoven geotextiles are best suited for use as filter materials.

The durability of a geotextile filter should be considered where the fabrics will be exposed to alkali or acidic soils, spilt fuels, etc. Geotextiles should not be used where they will be exposed to ultraviolet rays or sunlight. When the material will be subjected to severity of service or

harsh construction practices, its resistance to tear, puncture, and burst, as well as its tensile strength must be considered.

There is some question concerning the need for filter materials if an open graded drainage layer is constructed on stabilized subgrade soils. Several open graded subbase drainage layers have been constructed on lime stabilized subgrades in Illinois without use of a filter layer. This concept warrants further investigation relating to performance.

5.4.4 Longitudinal and Transverse Pavement Drains

Water that is collected in the pavement subbase drainage layer must be carried away from the pavement. This can be accomplished by daylighting the drainage layer at the shoulder or by positive collector systems. A positive collector system is preferred since daylighted drainage layers often become contaminated and clogged after construction.

Water from the subbase is best collected into transverse and longitudinal subdrainage systems. Subdrainage systems generally consist of a trench filled with granular material, a perforated pipe, and filter protection, or more recently by prefabricated geocomposite subdrainage systems (PGS systems). Figure 5.22 shows a conventional pipe and aggregate envelope subdrainage systems and Figure 5.23 shows a typical PGS system. A thorough discussion of PGS system can be found elsewhere in work by Dempsey (13,14).

For pipe and envelope subdrainage systems the trench width is generally twice the pipe diameter and ranges from about 8 in. to 12 in. wide. The trench depth for structural pavement drainage is normally 12 in. to 36 in. Trench depth is controlled somewhat by the pipe strength and depth of frost penetration. The permeability of the trench backfill envelope is important for a pipe system. Moulton (1) has provided the following expression for relating backfill permeability and trench width to inflow rate:

$$k_t = q_d/2b \qquad \text{(Eq. 5.20)}$$

where:

k_t = saturated permeability of the envelope material in ft/day

q_d = the net inflow into the pavement multiplied by the flow path length which is equivalent to the flow rate into the drain per linear foot of drain, in cfd/ft, and

$2b$ = trench width in ft.

The trench envelope material must also comply with the size of the slots or holes in the subdrainage pipe. These criteria are as follows (1):

(D_{85}) trench backfill > 0.5 times slot width (Eq. 5.21)

(D_{85}) trench backfill > 1 times hole diameter (Eq. 5.20)

The trench backfill should meet the filter criteria given in Eq. 5.15 through 5.19 as well.

Presently, several different types of drainage pipe of various lengths and diameters are being used in pavement subsurface drainage. Some of these are as follows:

1. Clay tile.

2. Concrete tile and pipe.

3. Vitrified clay pipe.

4. Perforated plastic bituminous fiber pipe.

5. Perforated corrugated-metal pipe.

6. Corrugated plastic tubing.

7. Prefabricated Geocomposite Subdrainage Materials.

The clay and concrete tile can be obtained in 1- to 3-ft (0.3 - to 0.9-m) lengths. Metal and fiber pipes are usually manufactured in lengths of 8 ft (2.4 m) or longer. The thick-walled, semi-rigid plastic tubing may be obtained in about 20-ft (6- m) lengths. The corrugated plastic tubing is manufactured in rolls about 200-ft to 300 ft (61m to 91 m) long. For subsurface drainage, the pipe diameter generally ranges between 4 in. and 6 in. (20 cm and 15 cm).

The prefabricated geocomposite subdrainage (PGS) materials are generally 1 in. to 1.5 in. in width and can be manufactured in numerous depths. The PGS material acts as both a collector and as a conduit for water. The PGS system can be placed in trenches 3 in. to 4 in. wide with little problem. If properly placed the PGS system doe not require a permeable envelope system for flow. In many cases backfill . consist of sand or excavated trench material. The top of the PGS system can be located very near the pavement surface with as little as 6 in. of cover in some traffic areas. One advantage of the PGS system is that the core remains open during frost penetration and therefore permits rapid drainage as soon as thaw begins.

Although subdrainage is normally associated with rigid pavements, it is also considered to be useful in promoting flexible pavement performance. Figure 5.24 shows a typical location for both a conventional pipe and envelope subdrainage system and a PGS system.

The pipe diameter required for the drain can be determined if the outlet spacing, design inflow rate, and pipe gradient are known. Flow nomographs based on Manning's flow equation can be developed as shown in Figure 5.25 for relating pipe size and outlet spacing to inflow rate and pipe gradient (15). Similar nomographs have been developed by Dempsey (16) for PGS systems as shown in Figures 5.26 and 5.27. The main problem with PGS systems is that flow characteristics relate heavily to the manufacturing process and core configuration. For this reason it is necessary to use a product specific nomograph for flow. It is also important to note in both Figures 5.26 and 5.27 that the depth of flow is provided in the PGS system as a function of inflow, outlet spacing, and flow gradient. This depth of flow relates to the flow zone depth shown in Figure 5.23. The actual depth of the PGS system is

based on the depth of water flow plus the subbase layer thicknesses and possibly the pavement surface thickness. This total thickness of the PGS system is required because it must act as both a collector of water and a conduit for flow.

A PGS system has an advantage in that it can be extended to considerable depth and satisfy several functions. Figure 5.28 shows an application of a PGS system to an airport taxiway where it serves a dual function of collecting water from the pavement structural section and controlling the water table depth.

The hydraulic flow requirement for PGS materials are determined under the guidelines of ASTM D4716-87. Based on this test it is recommended that the in-plane flow for airport pavements be greater than 20 gal/min/ft of width (based on a hydraulic gradient of 0.1 and specimen length of 24 in.) at a normal pressure of 15 psi. It is generally felt that the maximum compressive strength of the PGS material core should be in the area of 55 psi for airport construction. The geotextiles used on the PGS system should be a nonwoven material with adequate strength, durability, and hydraulic properties to function in the airport pavement environment.

5.4.5 Subdrainage Outlets

The outlet spacing should be established for various combinations of pipe size and gradient. Pipe outlet spacing should be no greater than 300 ft to 600 ft for cleaning and maintenance purposes. Pipes used for outlets do not have to be perforated and can be placed in a ditch backfilled with low permeability soil. All pipe and PGS material Tee, endcap, and splice connections must prevent intrusion of outside materials.

An important feature of the outlet system is the exit point. The pipe exit must be protected from natural and man-made hazards with the use of screens or valves, headwalls, and markers. Outlet markers should be used if they are to be easily spotted by maintenance personnel. Rodent screens similar to a 3x3 galvanized hardware cloth with .063 wire or equivalent is an absolute requirement on PGS systems and most subdrainage pipe. Outlets must be located in such a way as to prevent outside water from flowing back into the pavement subdrainage system.

5.5 Pavement Subsurface Drainage Design Models

5.5.1 General

Appendix A provides a computer code in basic language for a model named HSD3.BAS which was developed in this project for predicting water inflows and subsurface drainage requirements for pavement systems. This code has been subsequently expanded in an FHWA project by Carpenter (17) as a program named Drainage Analysis Modeling Program or DAMP. Although DAMP was developed for highway pavements it can easily be adapted to airport pavements as well. It is intended to be used as a supplement to the Highway Subdrainage Manual developed by Moulton (1).

The DAMP program is an assembly of a series of analysis routines that will allow the design engineer to evaluate the status of moisture related

areas in a pavement under investigation. This may be a new pavement, or it may be a pavement scheduled for rehabilitation. The purpose of this program is to provide the engineer with a comprehensive set of tools to conduct an evaluation of the pavement, the materials, and the environment to determine if there are concerns with moisture in the pavement.

5.5.2 Operating System

The program will run on PC-DOS compatible micros. It can be run under versions of DOS from version 2.1 to 4.0. It has been executed under the newest release of the OS/2 operating system, in the DOS mode.

5.5.3 Graphics

The system must have graphics capability, with the CGA standard being the minimum acceptable. A color monitor is highly recommended to take full advantage of the color used in the screens, and for the graphical screens in the program. The program will execute on a monochrome monitor, but graphics will not be allowed, and incompatibilities may develop with on-screen presentation of various color combinations.

5.5.4 Storage

The programs are contained on a 5.25 inch floppy diskette (1.2 Mb), and do not require a hard disk to execute. The program executes very well in a two floppy disk based system. The performance of the program is enhanced when the program is run from a hard disk, and this configuration is recommended.

5.5.5 System Memory

There must be a minimum of 370k RAM free to execute the program. This memory is in addition to that used by any resident programs which may be used for editing input files.

5.5.6 Output

The program stores the input data on either hard or floppy diskette as specified by the user. The calculated data are stored on diskette also, and can be printed in a report format to a printer connected to the parallel port.

5.5.7 Calculation Modules

The program performs the following calculations:

5.5.7.1 Water Sources

Surface infiltration (user selectable)

- Ridgeway procedure
- Cedergren procedure

Meltwater infiltration

- FAA soil classification procedure

Groundwater inflow (Cut)

With and without interceptor trenches

Depth of interceptor drains to lower watertable

Outflow (Fill)

Sloping or flat water table

High permeability layer at depth

5.5.7.2 Edge Drains

The program analyzes pipe drains, trench drains with no pipes, and the newest prefabricated geocomposite subdrainage materials, calculating depth of flow and outlet spacing using the most current laboratory data available from the University of Illinois.

5.5.7.3 Drainage Blanket

Drainage blankets are analyzed, depending on the available data the user has at hand. If permeability is not known, it will be estimated from the gradation data. The thickness of the material necessary to handle the amount of inflow is calculated and compared to the specified thickness for the pavement, allowing the engineer to alter the estimates based on the water handling capacity of the layer, as a supplement to the structural requirements. Alternatively, the required permeability can be determined for a preset thickness. These two calculations allow the engineer to make a decision when adjustments need to be made to handle the inflow.

5.5.7.4 Filtration

All untreated granular layers are examined to ensure they meet Casagrande filter requirements which ensure against plugging of the granular layers with intrusion of fines from the underlying layer. If a special granular material is to be used, such as in an edge drain trench, it is evaluated against the subgrade to determine if it is acceptable, or if a geotextile is needed. Geotextile recommendations are made following FHWA procedures to protect the aggregate from subgrade intrusion, depending on the characteristics of the installation.

5.5.7.5 Drainage Coefficient

AASHTO drainage coefficients are generated for all untreated granular layers for flexible and rigid pavements. The procedure adopted for this uses Thornthwaite climatic calculations which use actual temperature and rainfall data for the pavement location, and the actual material properties of the granular materials in the pavement. The time to drain the untreated granular materials is calculated using the gradation, density, thickness, and cross section parameters of the pavement. The percent of time in a year during which the pavement is exposed to moisture levels approaching saturation is calculated from monthly values of temperature and rainfall, which alter the total amount of moisture available in the area of a pavement. Suitable

REFERENCES

1. Moulton, L. K., "Highway Subdrainage Design," Report No. FHWA-TS-80-224, Federal Highway Administration, Washington, D.C., 1982.

2. Liu, S. J. and Lytton, R. L., "Environmental Effects on Pavements-Drainage Manual, Volume 4," Final Report, FHWA/RD-84/116, Federal Highway Administration, Washington, D.C., 1985.

3. Cedergren, H. R., Drainage of Highway and Airfield Pavements, John Wiley and Sons, New York, 1974.

4. "Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections," FHWA-RD-72-30, Federal Highway Administration, Washington, D.C., 1972.

5. Ridgeway, H. H., "Infiltration of Water through the Pavement Surface," Transportation Research Record 616, Transportation Research Board, Washington, D.C., 1976.

6. Dempsey, B. J. and Robnett, Q. L., "Influence of Precipitation, Joints, and Sealing on Pavement Drainage," Transportation Research Record 705, Transportation Research Board, Washington, D.C., 1979.

7. Kaplar, C. W., "A Laboratory Freezing Test to Determine the Relative Frost Susceptibility of Soils," Technical Report TR250, Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, Hanover, N.H., 1974.

8. Lytton, R. L., Pirfahl, D. E., Michalik, C. H., Liang, H. S., and Dempsey, B. J., "An Integrated Model of the Climatic Effects on Pavements," Final Report, FHWA RD-90-033, Federal Highway Administration, Washington, D.C., 1990.

9. Carpenter, S. H., Darter, M. I., and Dempsey, B. J., "A Pavement Moisture Accelerated Distress (MAD) Identification System," Vol. 1, Report No. FHWA/RD-81/079, Federal Highway Administration, Washington, D.C., 1981.

10. Casagrande, A. and Shannon, W. L., "Base Course Drainage for Airport Pavements," ASCE Proceedings, Vol. 77, 1951.

11. Dempsey, B. J. and Crovetti, J., "Pavement Subbases-IHR 525," University of Illinois, Urbana, Illinois, 1990.

12. Koerner, R. M., Designing with Geosynthetics, Prentice Hall, Englewood Cliffs, N.J., 1990.

13. Dempsey, B. J., "Core Flow Capacity Requirements of Geocomposite Fin-Drain Materials Utilized in Pavement Drainage," Transportation Research Record No. 1159, Transportation Research Board, Washington, D.C., 1988.

adjustments are made for poor cross section selections (bath tub sections), or improved material selections (stabilized subbases for example).

5.6 Summary

In this section the sources of water which influence pavement subdrainage have been identified and quantified. The various types of subsurface drainage systems have been described and procedures for designing the subsurface drainage system presented. Procedures for designing both conventional pipe and envelope subdrains and prefabricated geocomposite subdrainage (PGS) systems have been discussed. A comprehensive drainage model designated as DAMP which can be obtained from the FHWA was described. Although this section recommended an open graded drainage blanket for subbase drainage, both transverse and longitudinal subdrainage systems can be beneficial to drainage of pavements on dense subbase layers. Considerable amounts of water can pass along the interfaces of the various pavement layers. If not drained, this water can be a major contributor to pavement distress.

14. Dempsey, B. J., "Hydraulic REquirements of Geocomposite Fin-Drain Materials Utilized in Pavement Subdrainage," Geotextiles and Geomembranes Journal, Vol. 8, Elsevier Applied Science Publishers, United Kingdonm, 1989.

15. Cedergren, H. R., Seepage, Drainage, and Flow Nets, John Wiley and Sons, New York, 1989.

16. Dempsey, B. J., "Unpublished Data from Laboratory Testing," University of Illinois, Urbana, Illinois, 1989.

17. Carpenter, S. H., "Highway Subdrainage Design by Microcomputer DAMP User's Guide and Technical Guide," FHWA-IP-90-012, Federal Highway Administration, Washington, D.C., 1990.

Table 5.1 Guidelines for Selection of Heave Rate on Frost Susceptibility Classification (Ref. 1).

Unified Classification Soil Type	Symbol	Percent < 0.02 mm	Heave Rate mm/day	Frost Suscept. Classification
Gravels and Sandy Gravels	GP	0.4	3.0	Medium
	GW	0.7-1.0	0.3-1.0	Neg. to Low
		1.0-1.5	1.0-3.5	Low to Medium
		1.5-4.0	3.5-2.0	Medium
Silty and Sandy Gravels	GP-GM	2.0-3.0	1.0-3.0	Low to Medium
	GW-GM	3.0-7.0	3.0-4.5	Medium to High
	GM			
Clayey and Silty Gravels	GW-GC	4.2	2.5	Medium
	GM-GC	15.0	5.0	High
	GC	15.0-30.0	2.5-5.0	Medium to High
Sands and Gravely Sands	SP	1.0-2.0	0.8	Very Low
	SW	2.0	3.0	Medium
Silty and Gravely Sands	SP-SM,	1.5-2.0	0.2-1.5	Neg. to Low
	SW-SM,	2.0-5.0	1.5-6.0	Low to High
	SM	5.0-9.0	6.0-9.0	High to Very High
		9.0-22.0	9.0-5.5	
Clayey and Silty Sands	SM-SC	9.5-35.0	5.0-7.0	High
	SC			
Silts and Organic Silts	ML-OL,	23.0-33.0	1.1-14.0	Low to Very High
	ML	33.0-45.0	14.0-25.0	Very High
		45.0-65.0	25.0	Very High
Clayey Silts	ML-CL	60.0-75.0	13.0	Very High
Gravely and Sandy Clays	CL	38.0-65.0	7.0-10.0	High to Very High
Lean Clays	CL	65.0	5.0	High
	CL-OL	30.0-70.0	4.0	High
Fat Clays	CH	60.0	0.8	Very Low

Table 5.2 Coarse Aggregate Gradations for Open Graded Subbase Drainage Layers.

Sieve Size / Gradation No.	Percent Passing								
	1 1/2"	1"	3/4"	1/2"	3/8"	No. 4	No. 16	No. 50	No. 200
CA 7	100	95±5	-	45±15	-	5±5	-	-	-
CA 11		100	92±8	45±15	-	6±6	3±3	-	-

Table 5.3 Open Graded Aggregate Gradations Used by New Jersey DOT and Pennsylvania DOT.

New Jersey DOT

Sieve Size	Percent Passing NSOG	Percent Passing BSOG*
1 1/2 in.	100	100
1 in.	95-100	95-100
1/2 in.	60-80	85-100
No. 4	40-55	15-25
No. 8	5-25	2-10
No. 16	0-8	2-5
No. 50	0-5	-
No. 200	-	2% Filler

*BSOC = Bituminous Stabilized Open Graded

Penn DOT

Sieve Size	% Passing
2 in.	100
3/4 in.	52-100
3/8 in.	36-65
No. 4	8-40
No. 16	0-12
No. 30	0-8
No. 200	0-5

Table 5.4 Percentage Index of Free Draining Water for Different Type of Base Courses (Ref. 9).

AMOUNT OF FINES	<2.5% FINES			5% FINES			10% FINES		
TYPE OF FINES	INERT FILLER	SILT	CLAY	INERT FILLER	SILT	CLAY	INERT FILLER	SILT	CLAY
GRAVEL	70	60	40	60	40	20	40	30	10
SAND	57	50	35	50	35	15	25	18	8

* Gravel, 0% fines, 75% greater than #4: 80% water loss.
* Sand, 0% fines, well graded: 65% water loss.
* Gap graded material will follow the predominant size.

Table 5.5 Filter Criteria for Geotextiles (Ref. 12).

Least Conservative

Soil $\leq$ 50% passing the No. 200 sieve

AOS of the fabric $\geq$ No. 30 sieve (i.e., $O_{95} < 0.59$ mm)

Soil > 50% passing the No. 200 sieve

AOS of the fabric $\geq$ No. 50 sieve (i.e., $O_{95} < 0.297$ mm)

More Conservative

$O_{95} < (2 \text{ or } 3)\ d_{85}$

Most Conservative

Relative Density	1 < CU < 3	CU > 3
Loose (D_R < 50%)	$O_{95} < (CU)(d_{50})$	$O_{95} < (9d_{50})/CU$
Intermediate (50% < D_R < 80%)	$O_{95} < 1.5(CU)(d_{50})$	$O_{95} < (13.5d_{50})/CU$
Dense (D_R > 80%)	$O_{95} < 2(CU)(d_{50})$	$O_{95} < (18d_{50})/CU$

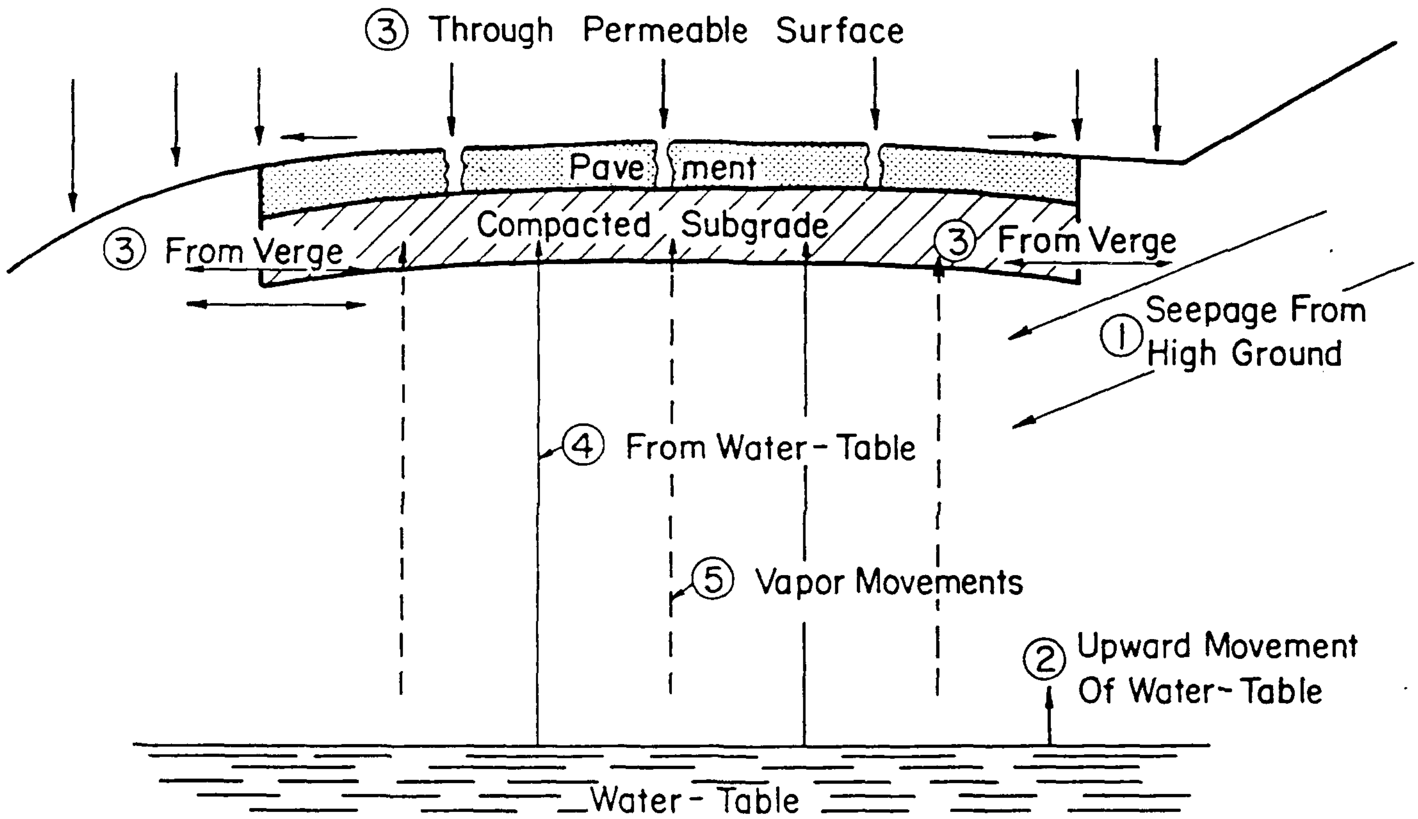


Figure 5.1 Water Sources in Pavements.

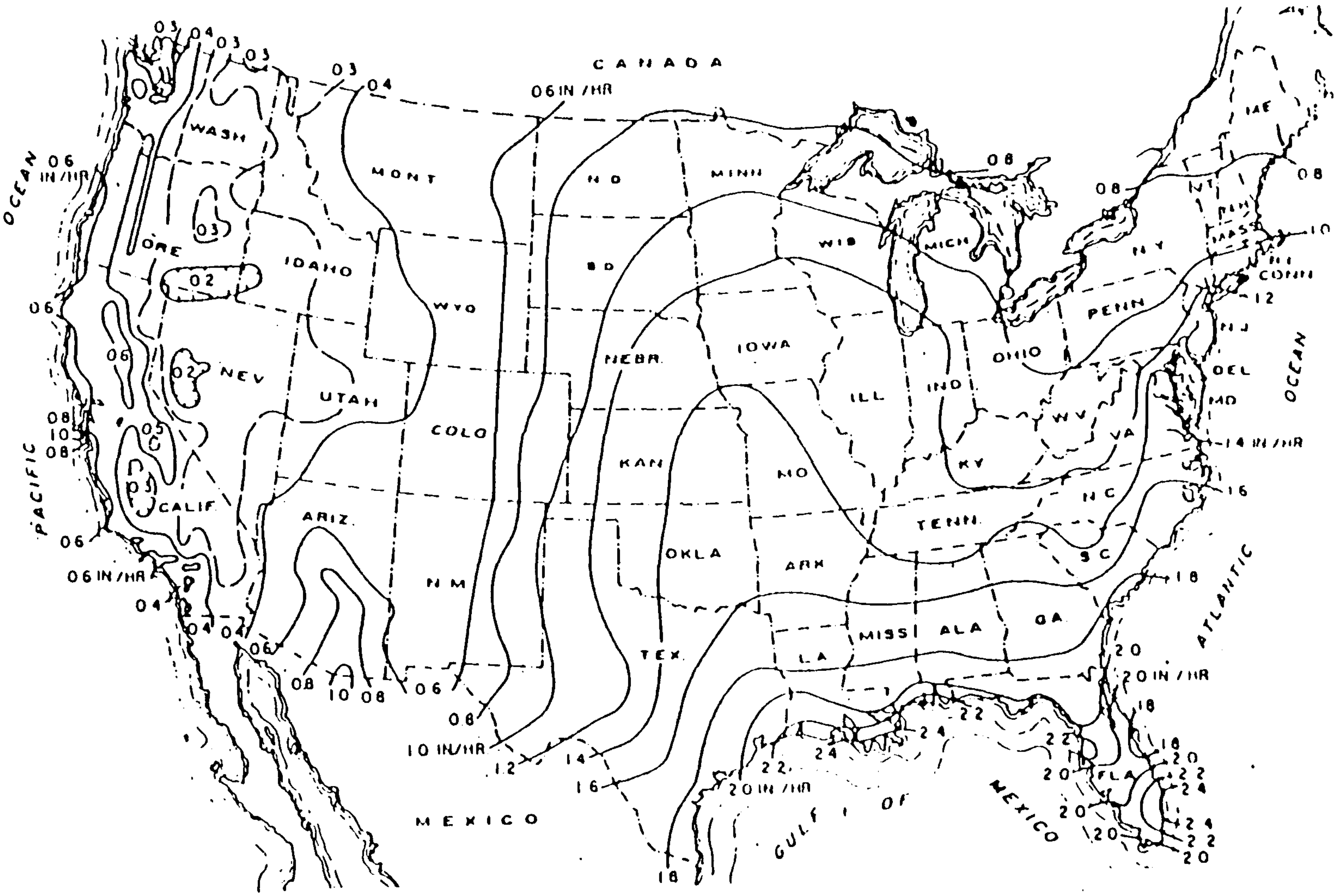


Figure 5.2 One Hour Rainfall with a One Year Frequency of Occurrence (Ref. 3).

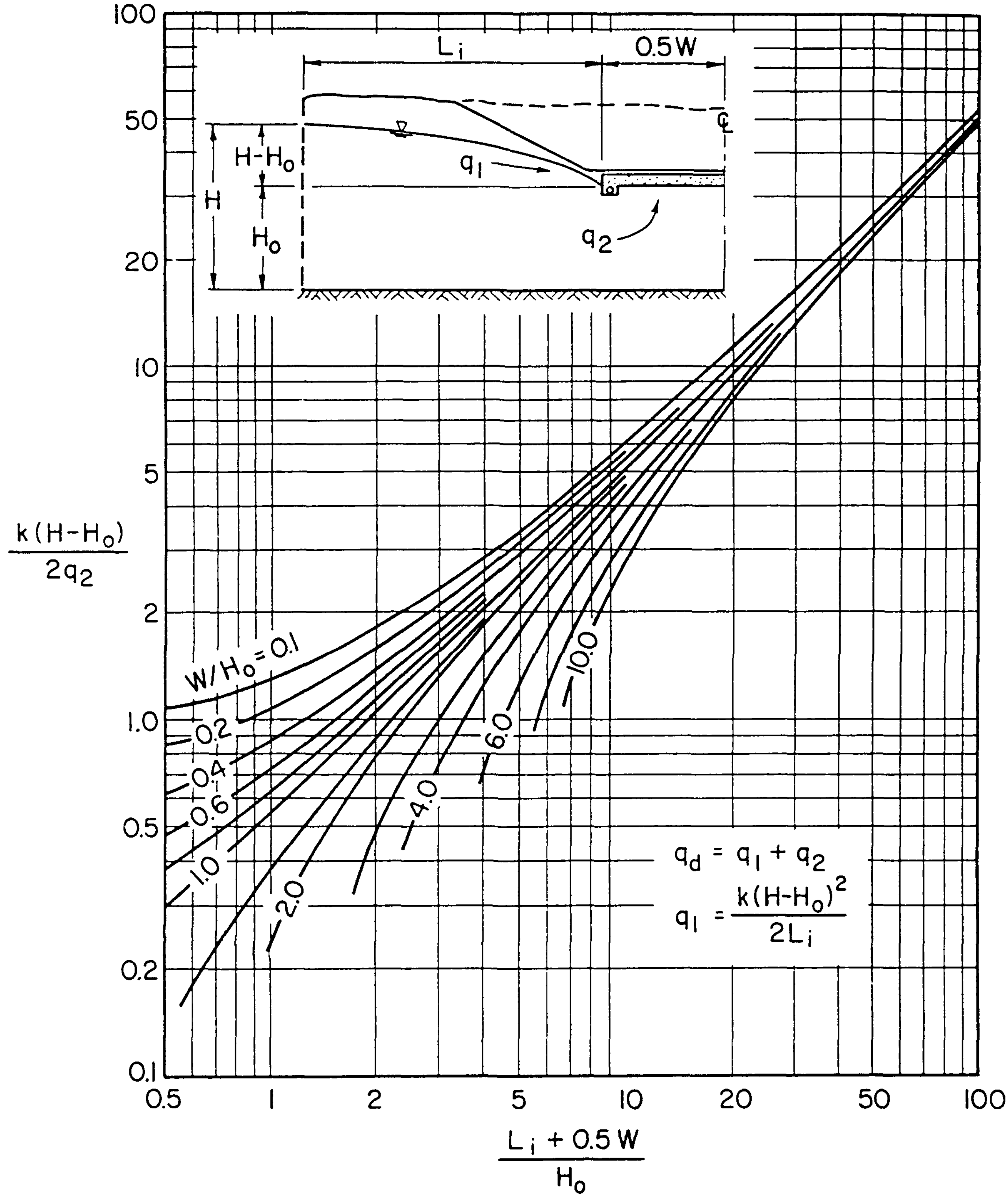


Figure 5.3 Gravity Flow of Groundwater into a Pavement System (Ref. 1).

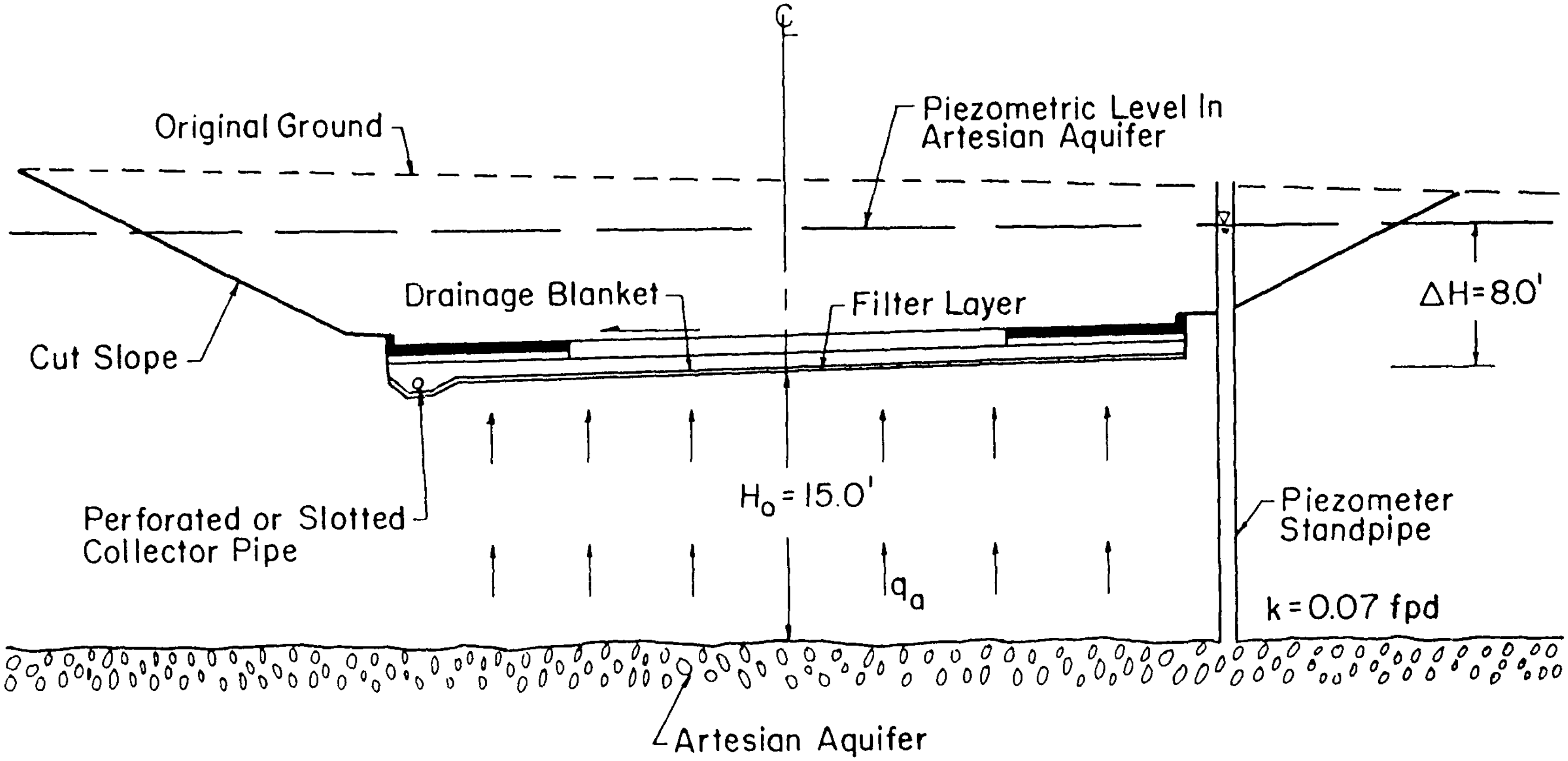


Figure 5.4 Artesian Flow into a Pavement System (Ref. 1).

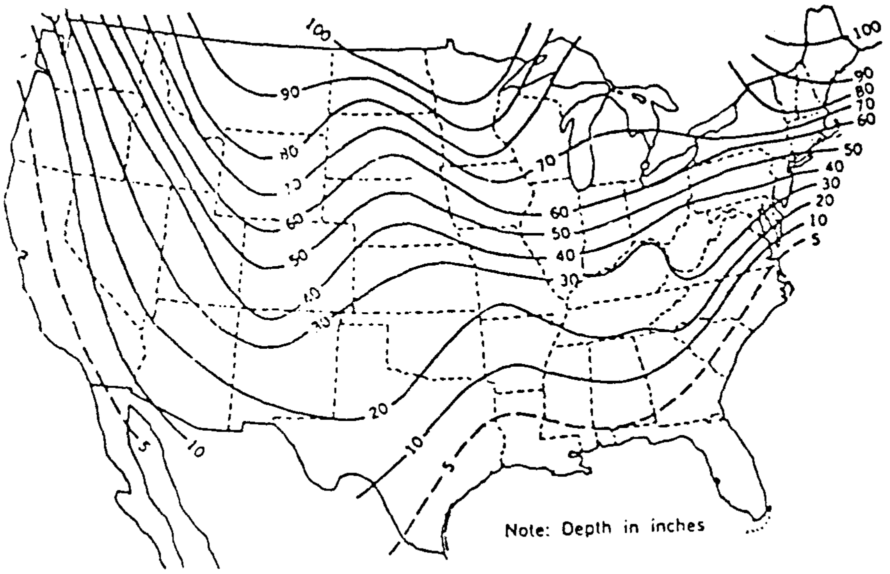


Figure 5.5 Maximum Frost Depth in the United States (Ref. 1).

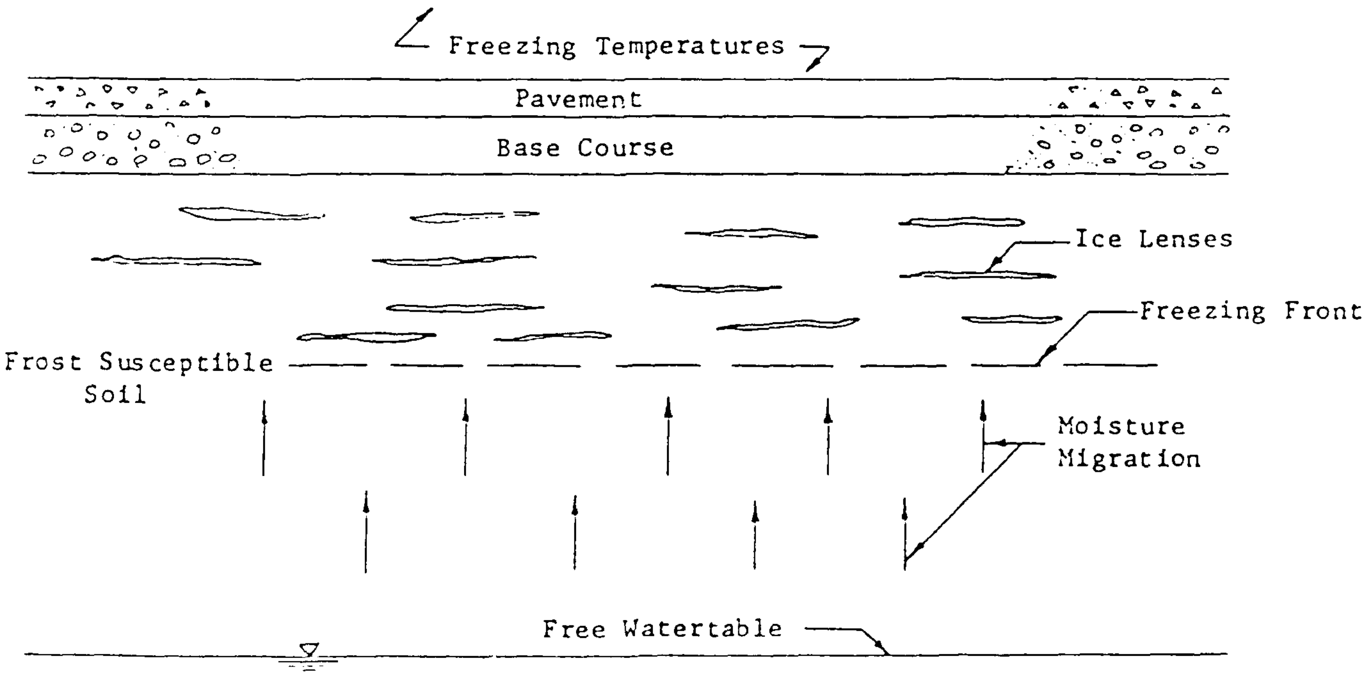


Figure 5.6 Capillary Moisture Movement to a Freezing Front Causing Ice Lense Formation (Ref. 1).

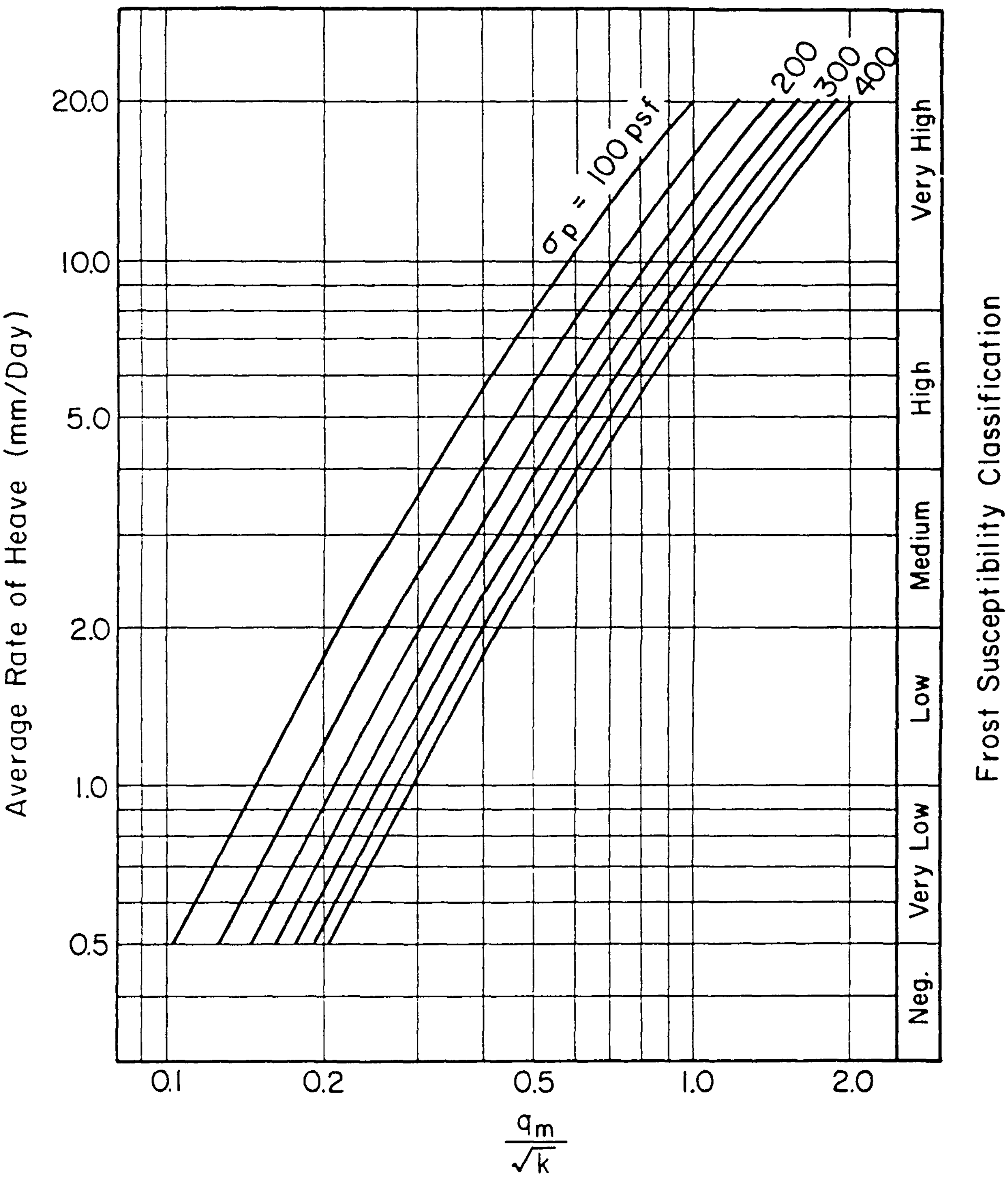


Figure 5.7 Chart for Estimating Inflow from Ice Lense Melt Water (Ref. 1).

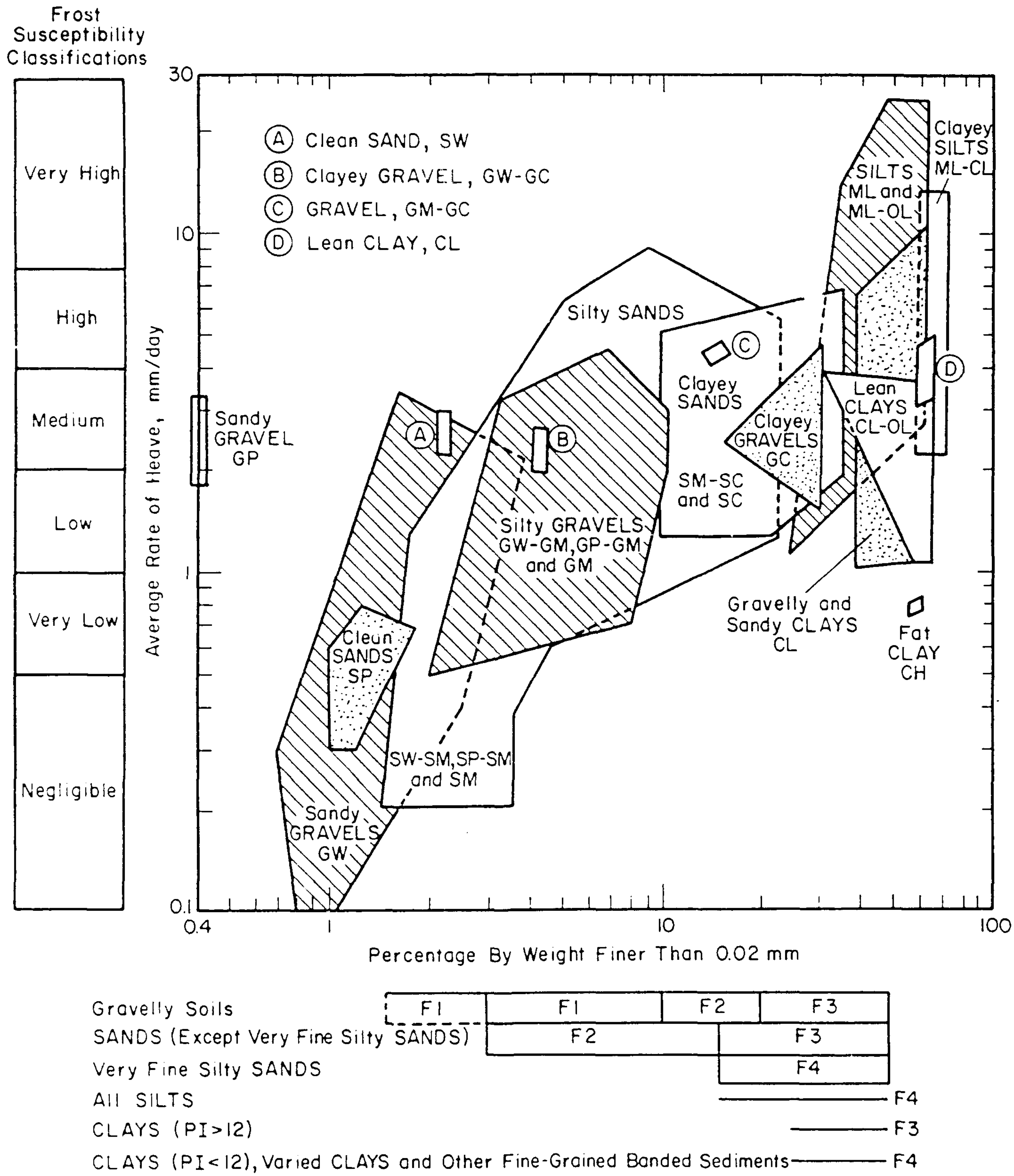


Figure 5.8 Corps of Engineers Procedure for Estimating Soil Frost Susceptibility (Ref. 7).

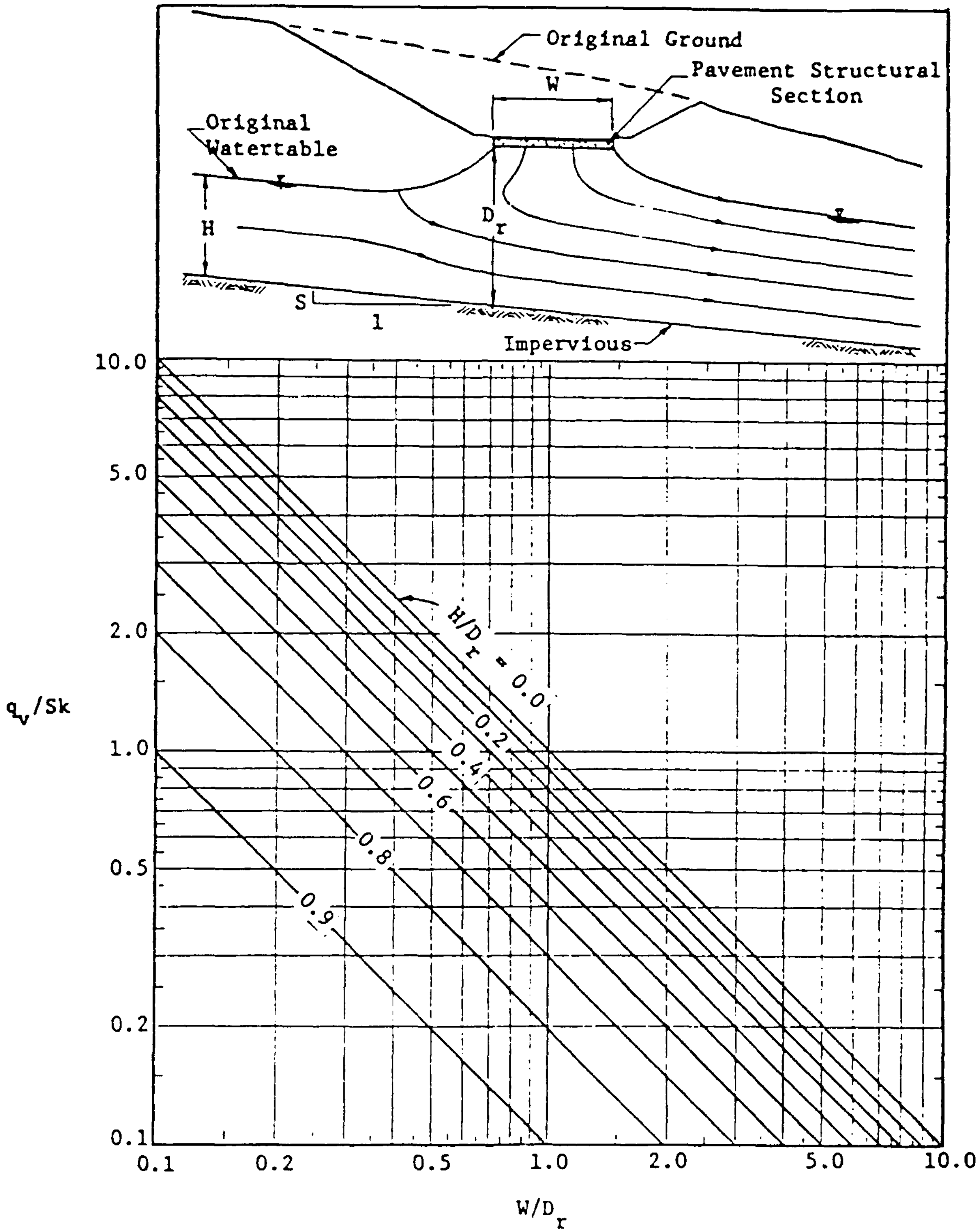


Figure 5.9 Chart for Estimating Vertical Outflow from Pavement Structural Section Through Subgrade Soil to a Sloping Underlying Watertable (Ref. 1).

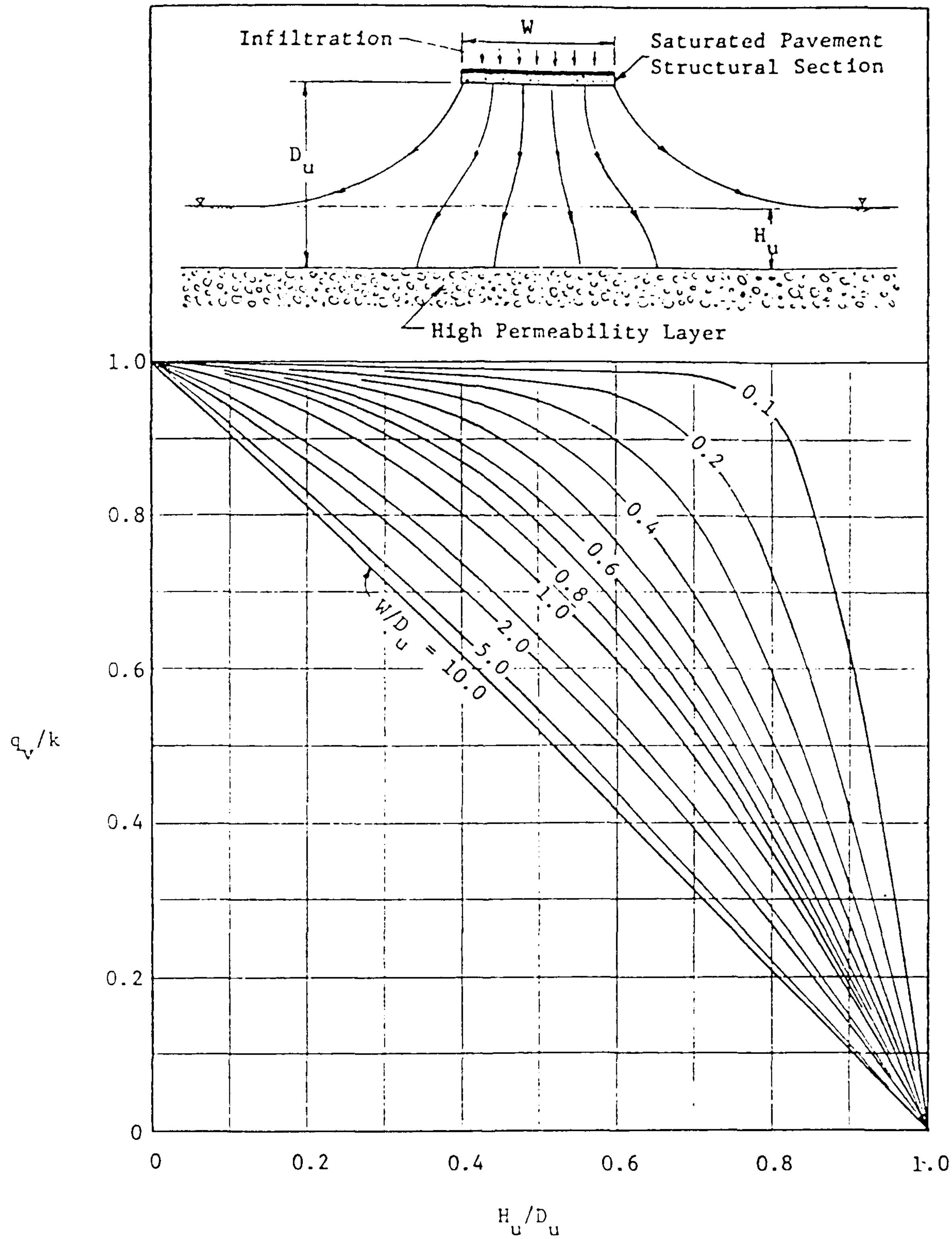


Figure 5.10 Chart for Estimating Vertical Outflow from a Pavement Structural Section Through the Subgrade to an Underlying High Permeability Layer (Ref. 1).

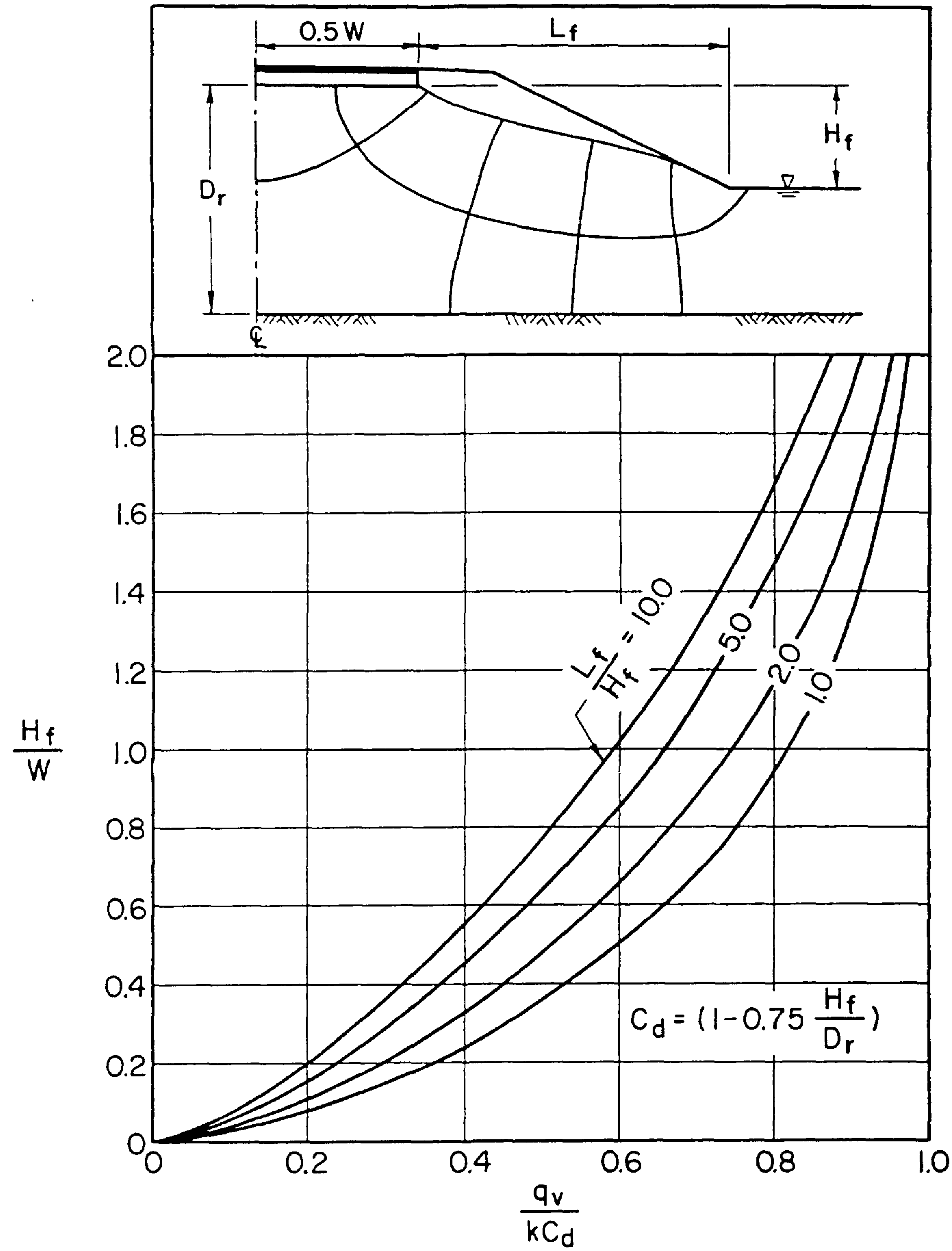


Figure 5.11 Chart for Estimating Vertical Outflow from a Pavement Structural Section through the Embankment and Foundation Soil (Ref. 1).

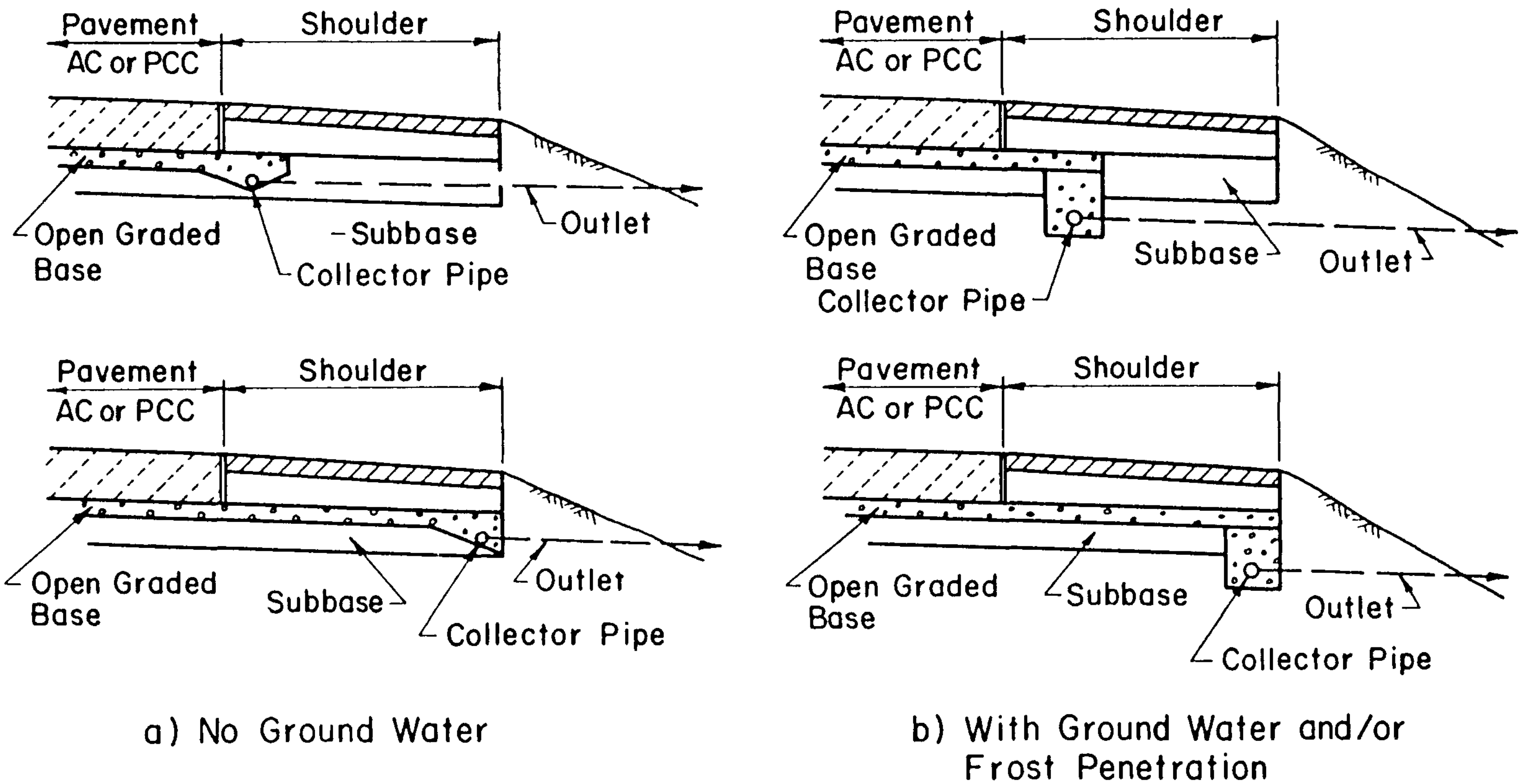


Figure 5.12 Typical Longitudinal Pavement Subsurface Drainage Systems.

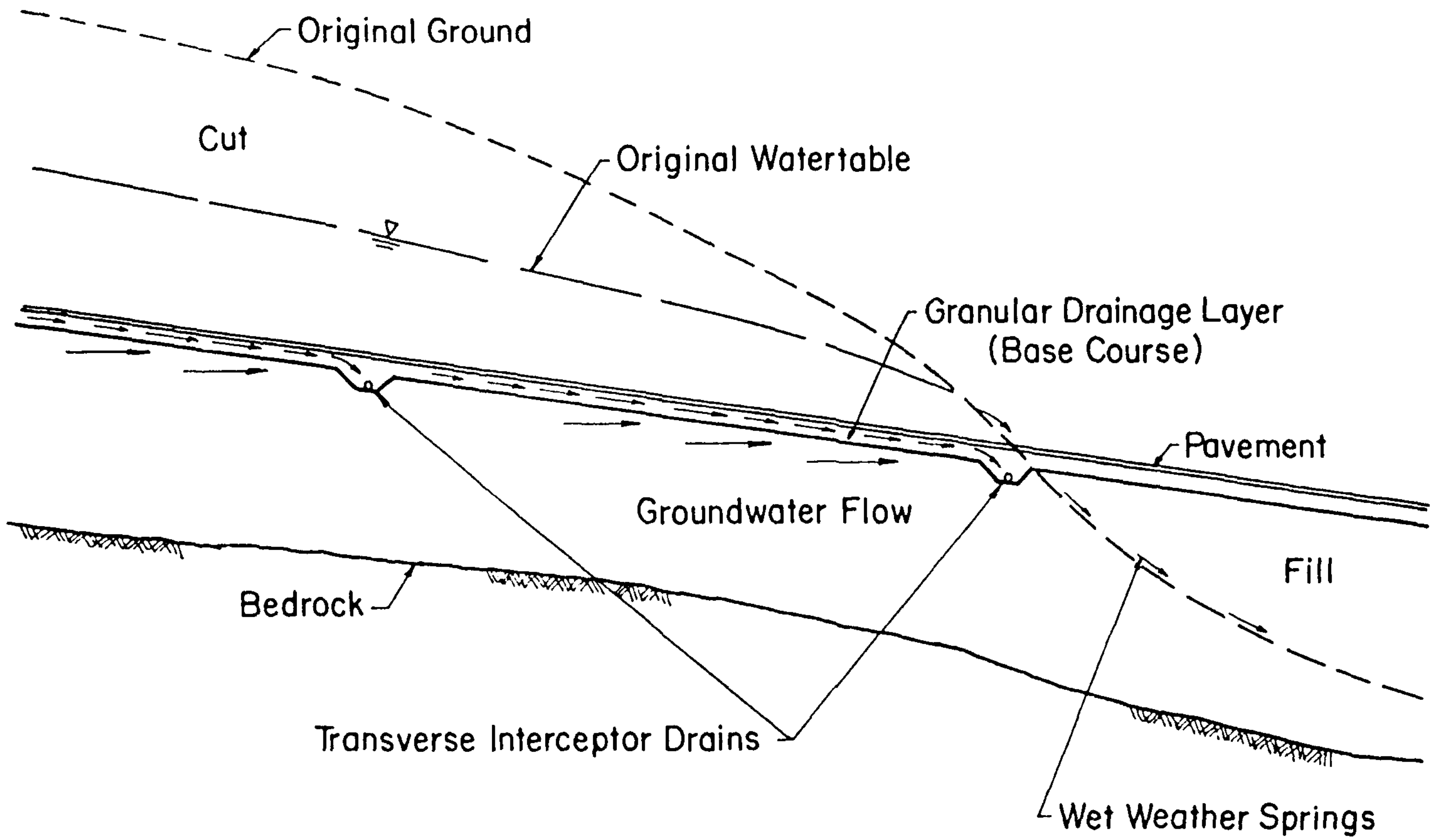


Figure 5.13 Transverse Pavement Subsurface Drainage System (Ref. 1).

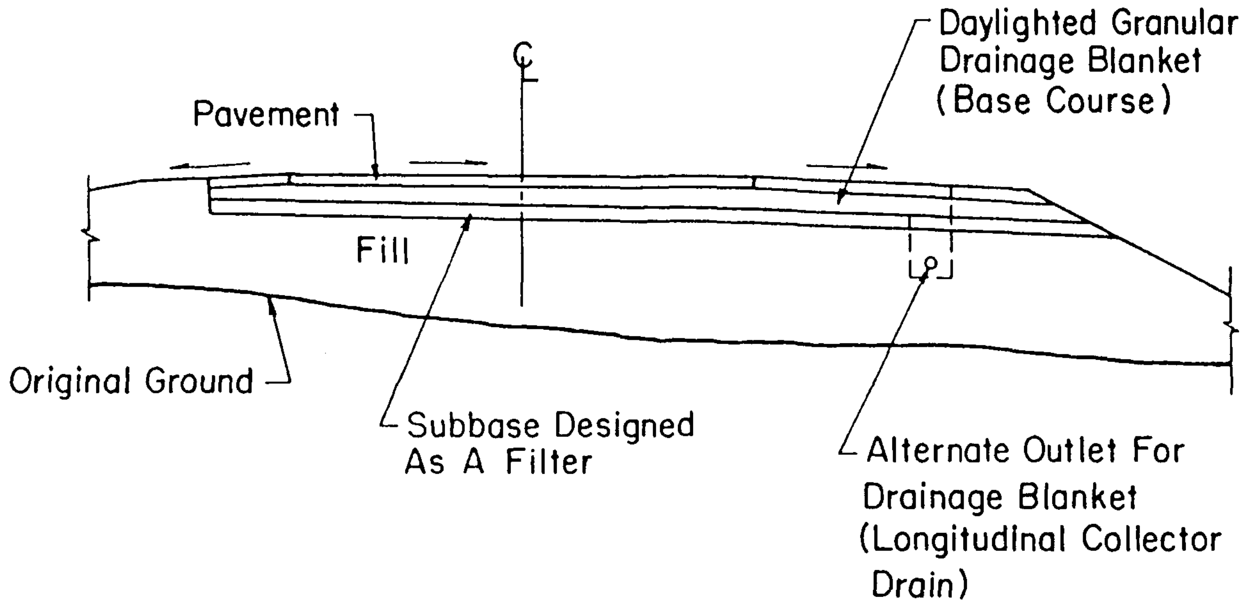


Figure 5.14 Example of a Pavement Subbase Drainage Blanket (Ref. 1).

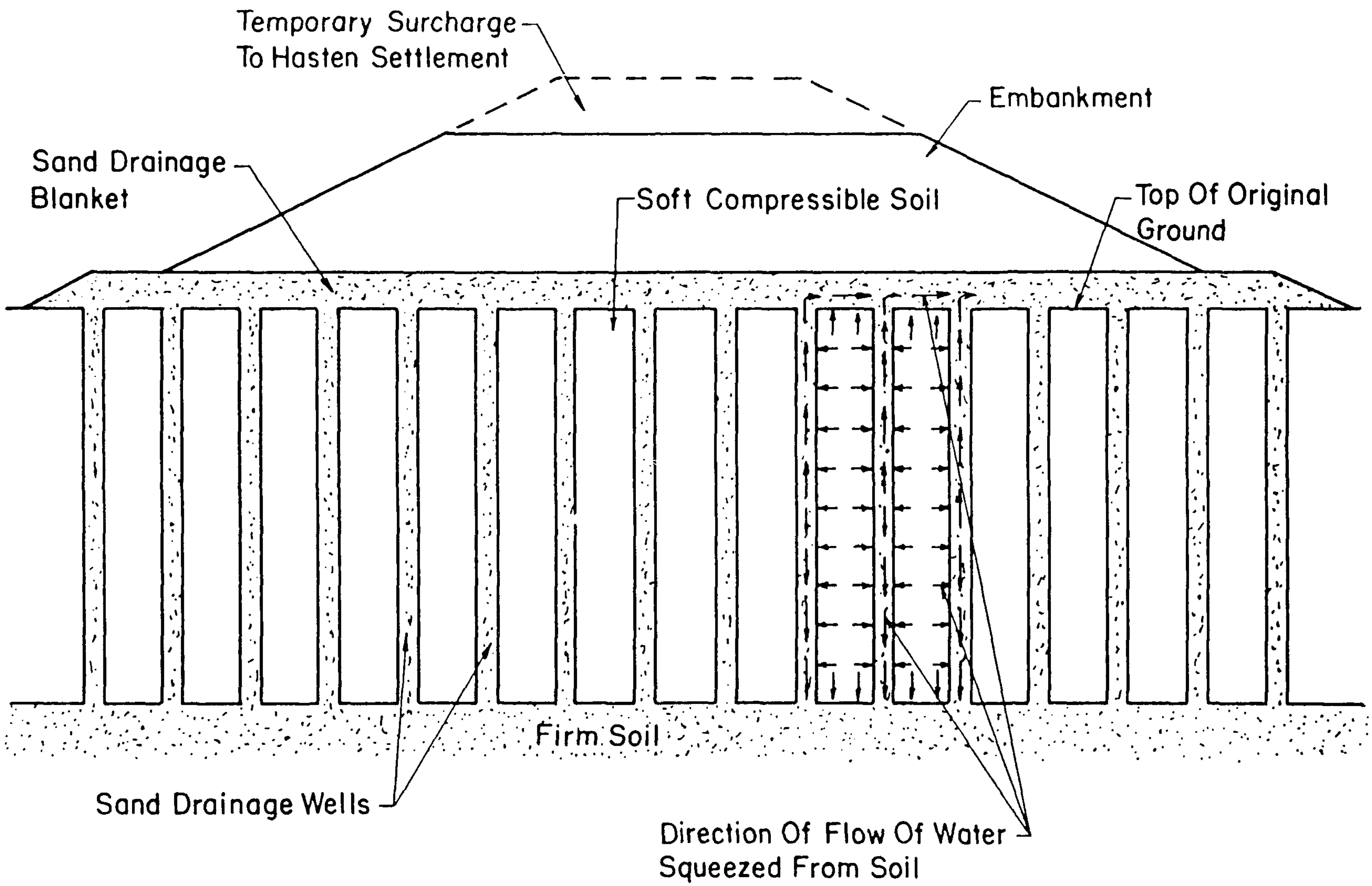


Figure 5.15 Typical Sand Drain Well System (Ref. 1).

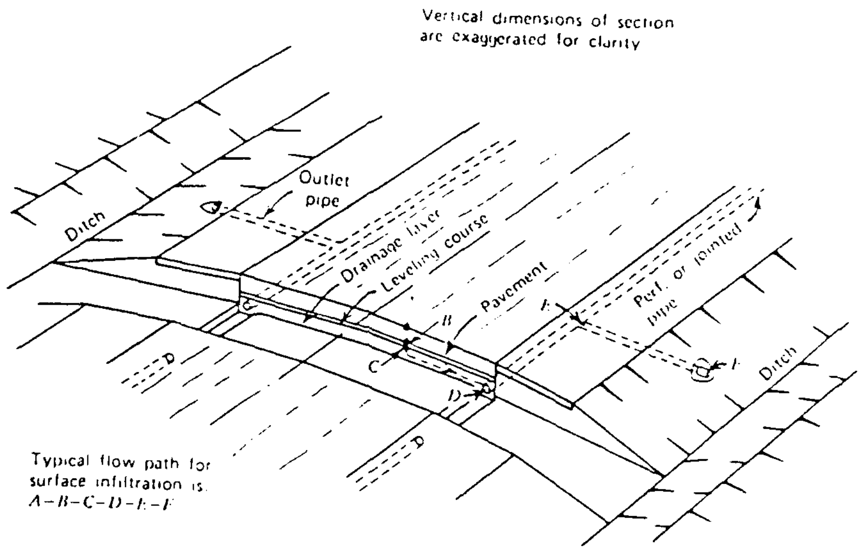


Figure 5.16 Illustration of Flow Path for Condition of Continuity in Pavement Drainage of Surface Infiltration (Ref. 3).

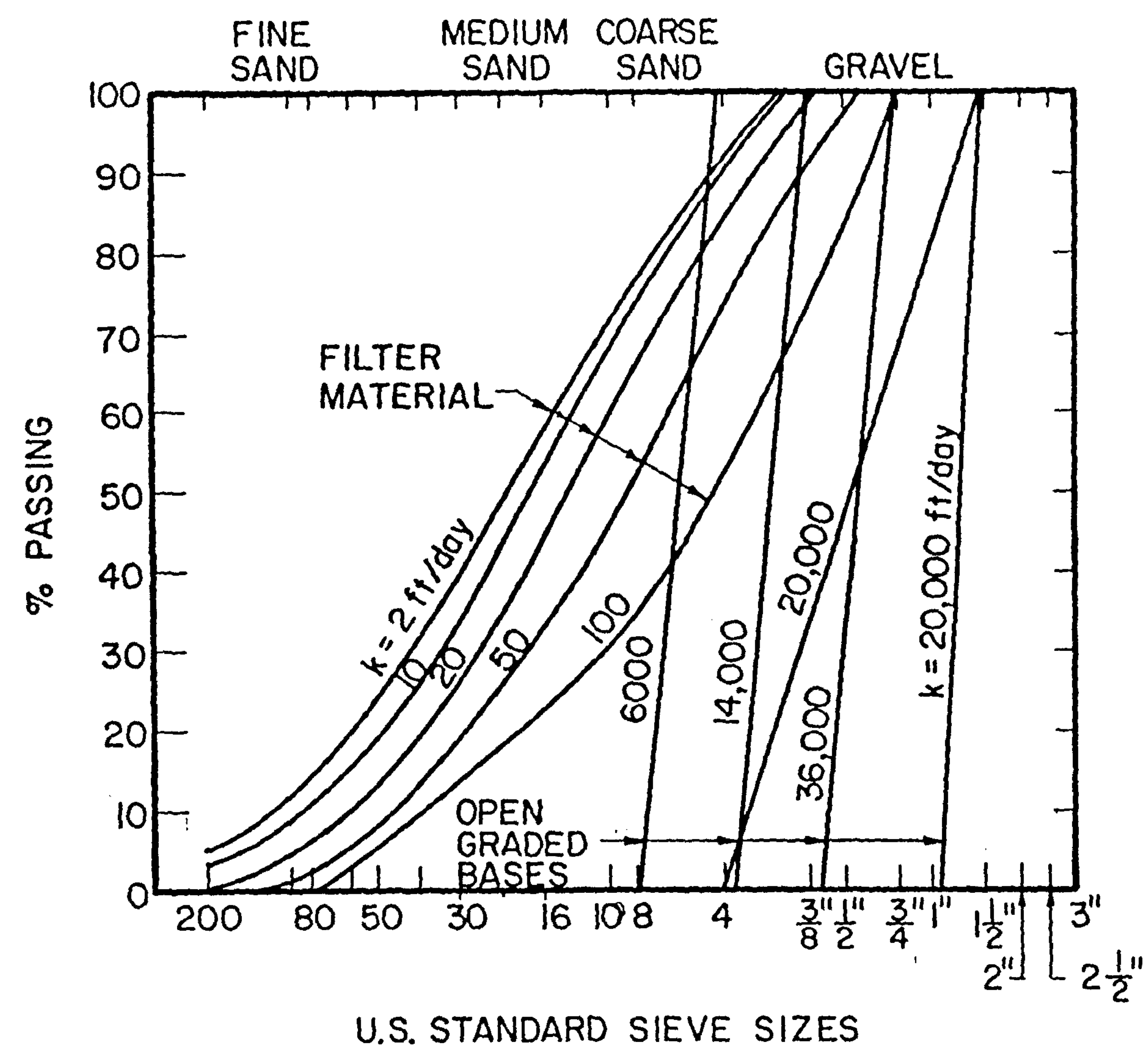


Figure 5.17 Effects of Grain Size Distribution on Permeability (Ref. 3).

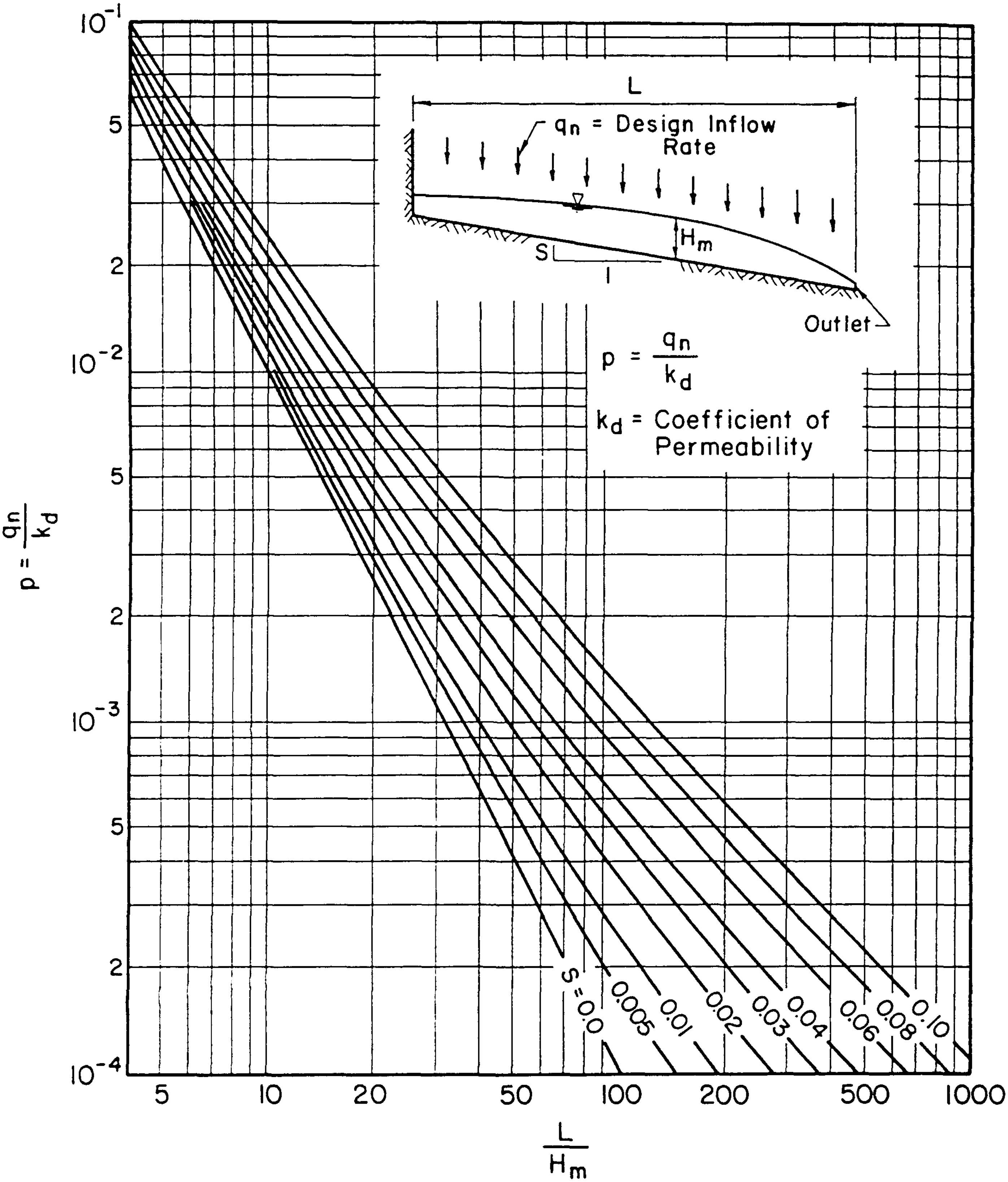


Figure 5.18 Chart for Estimating Maximum Depth of Flow Caused by Inflow (Ref. 1).

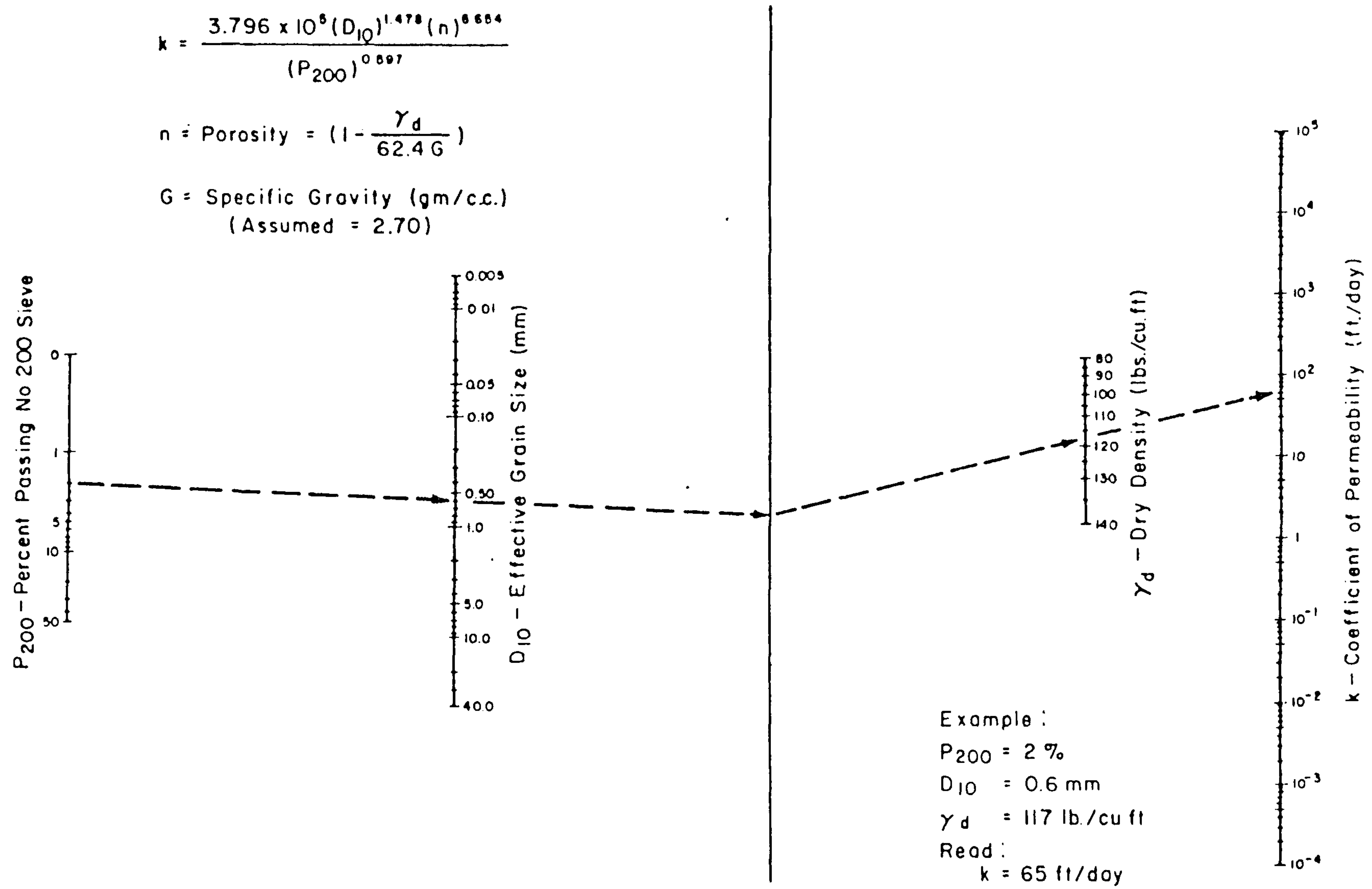


Figure 5.19 Nomograph Procedure for Estimating the Saturated Permeability of Granular Materials (Ref. 1).

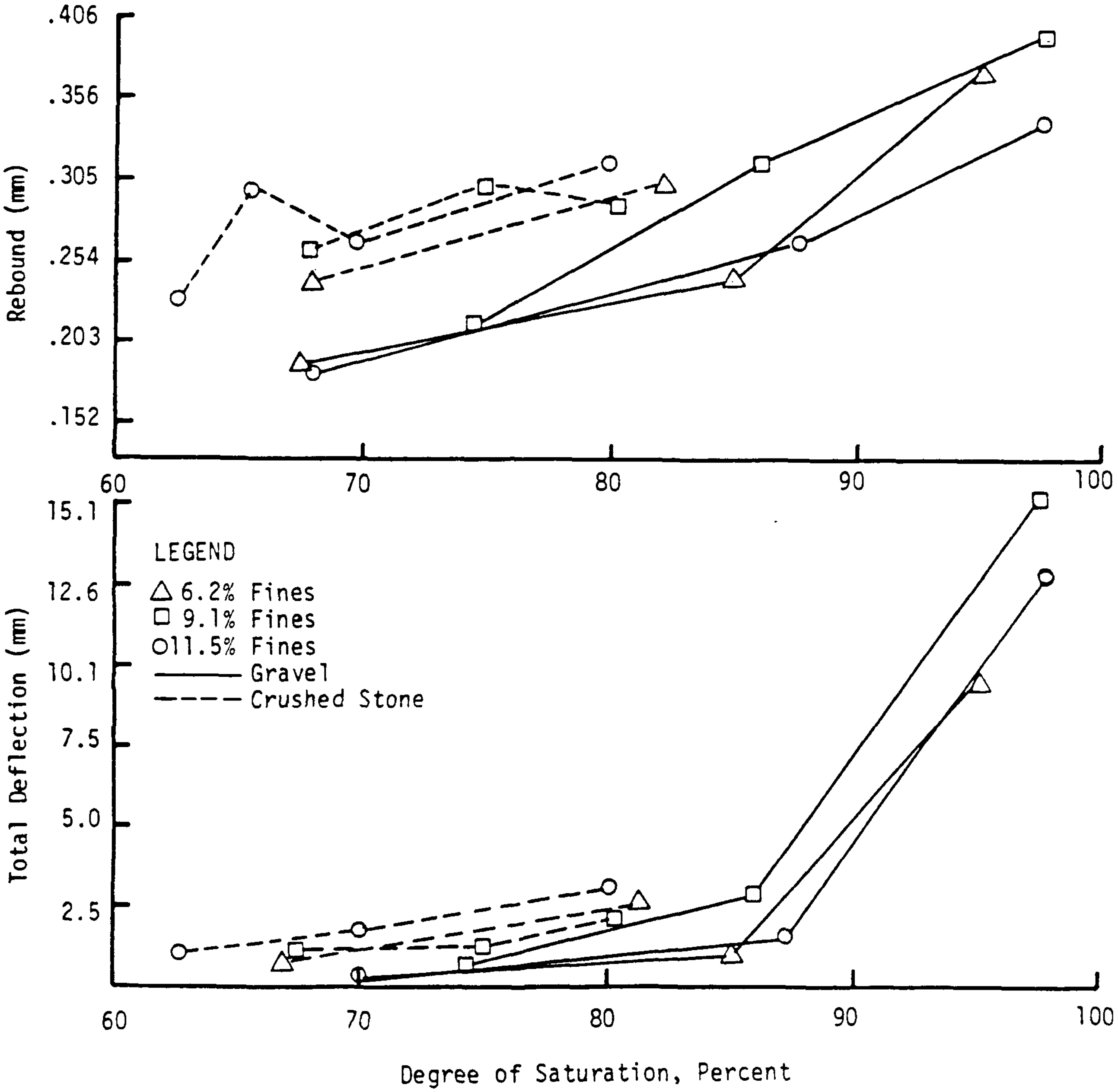


Figure 5.20 Influence of the Degree of Saturation on Deformation Properties of Granular Materials (Ref. 9).

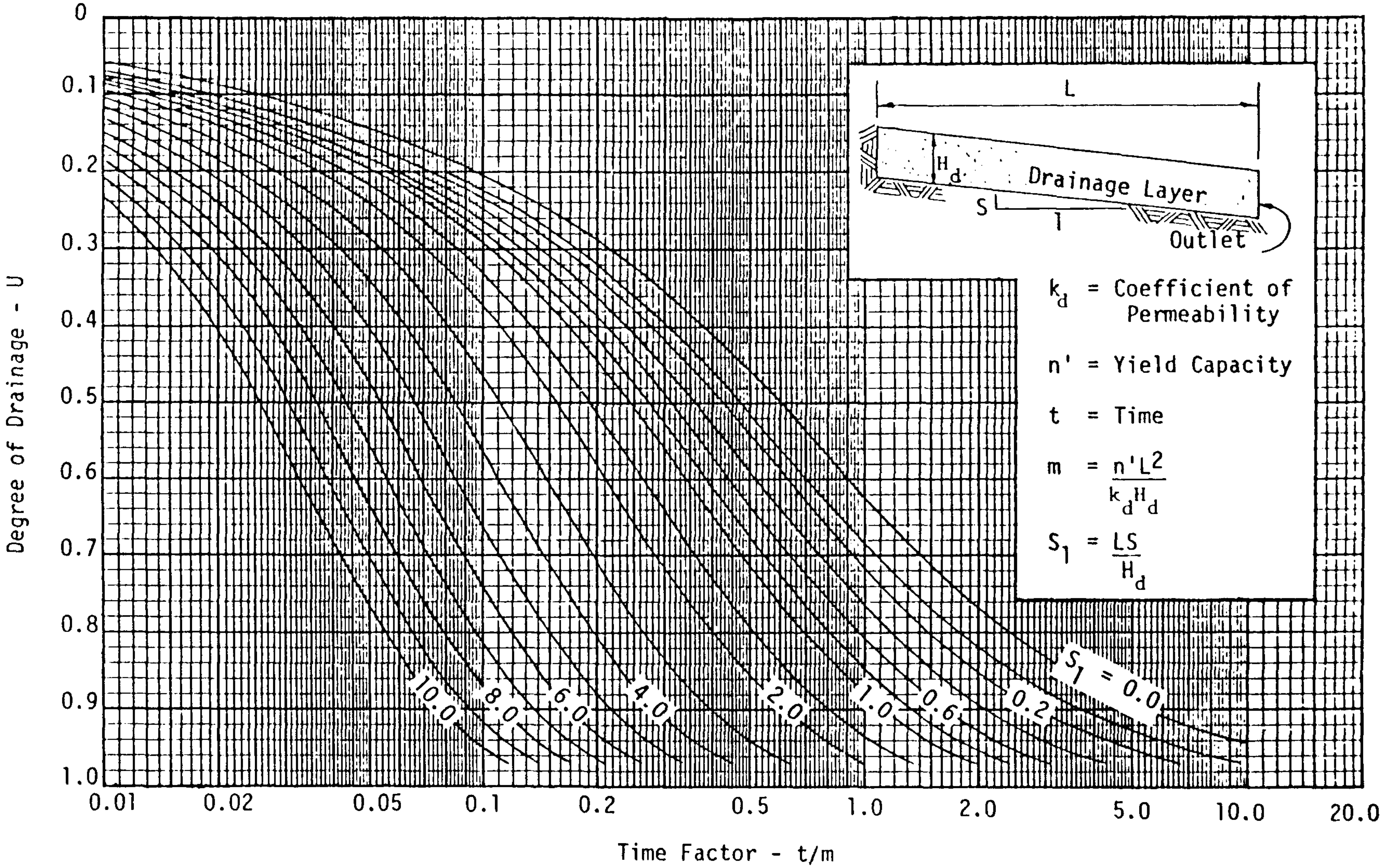


Figure 5.21 Time Factors for Degree of Drainage (Ref. 10).

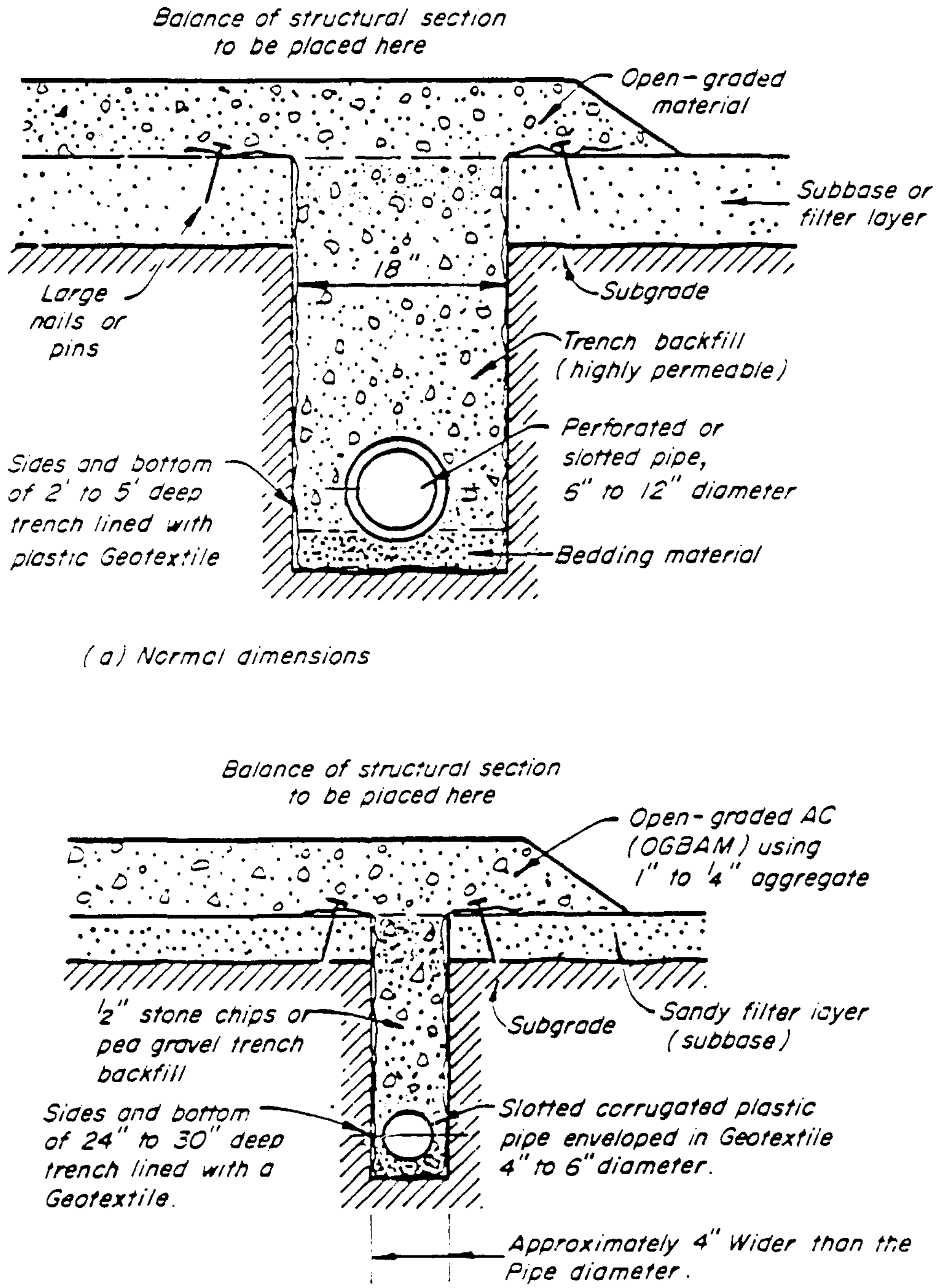


Figure 5.22 Conventional Pipe Underdrain System (Ref. 3).

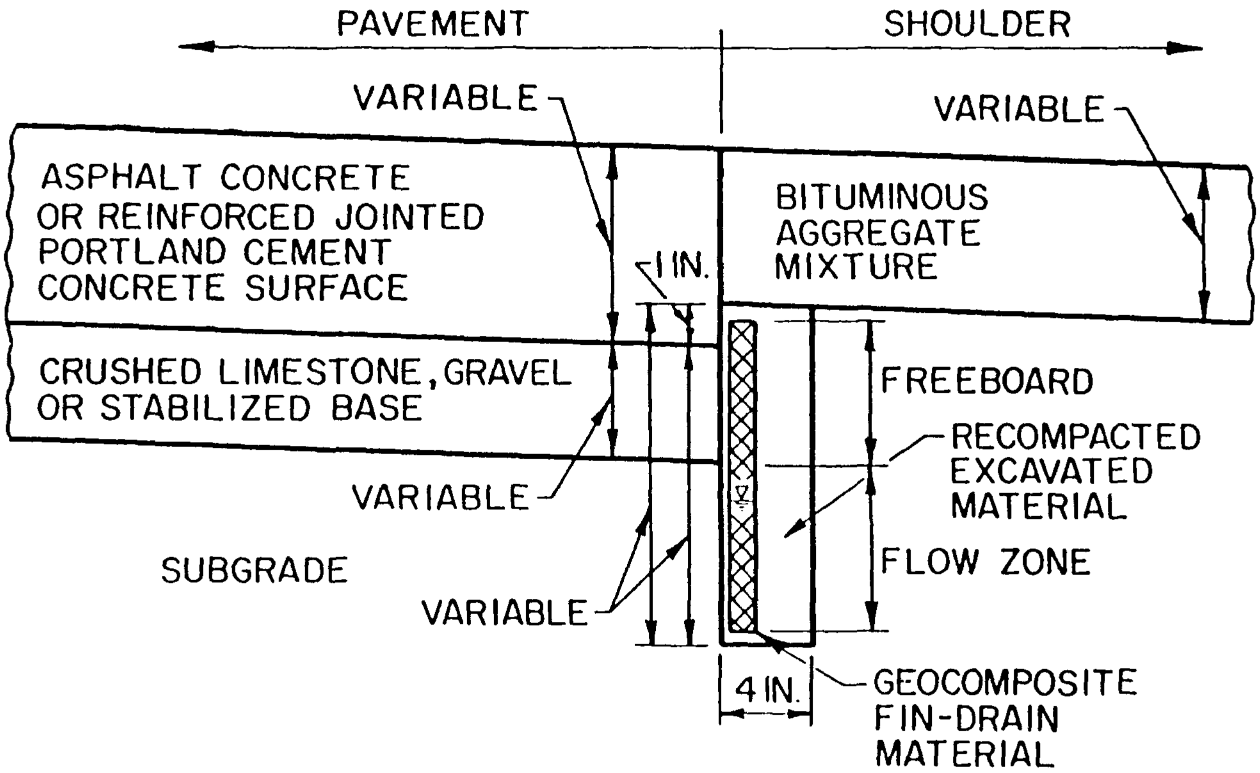


Figure 5.23 Typical Prefabricated Geocomposite Subdrainage System.

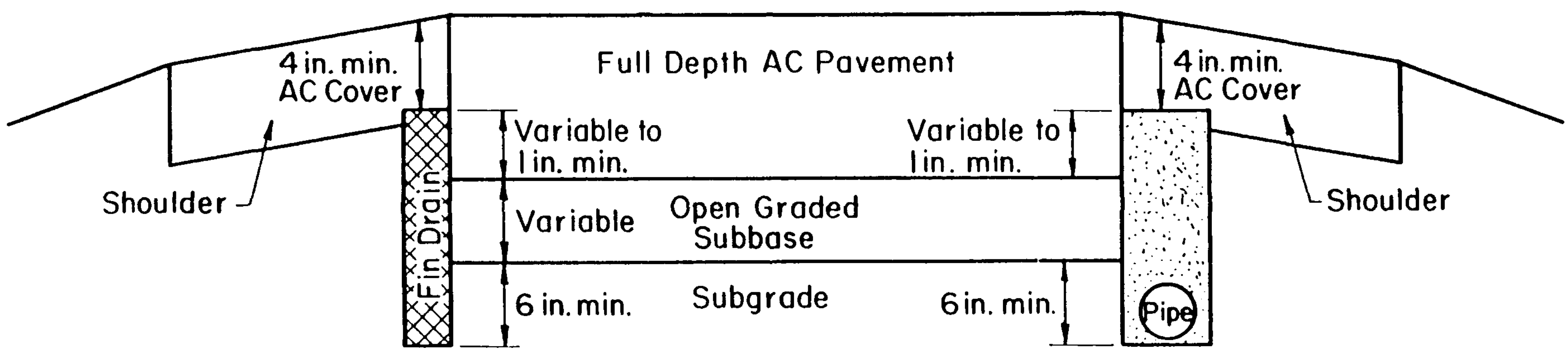


Figure 5.24 Subsurface Drainage System Location in Asphalt Concrete Pavements.

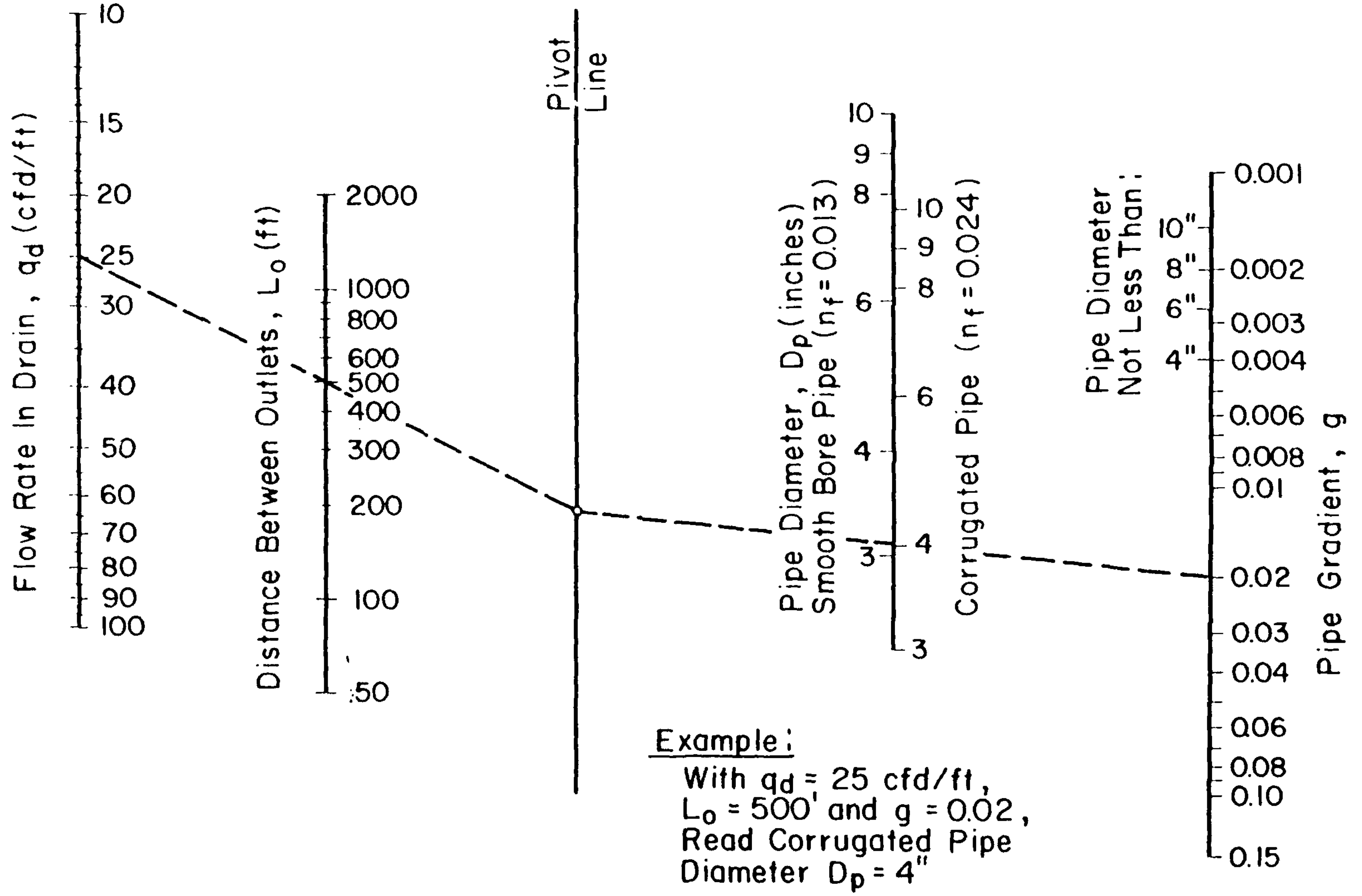


Figure 5.25 Flow Nomograph for Circular Pipe (Ref. 15).

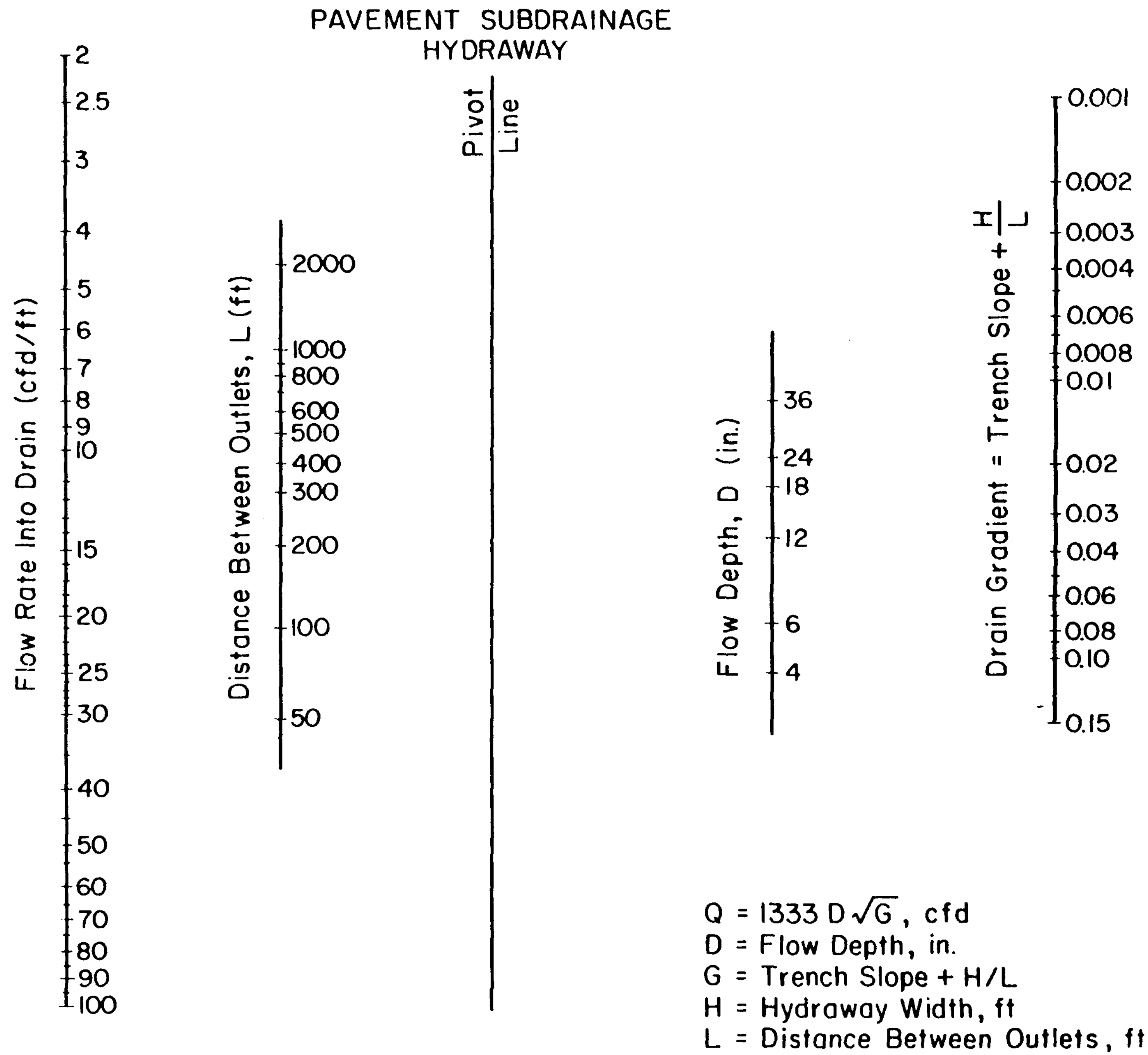


Figure 5.26 Typical Flow Nomograph for HYDRAWAY 2000.

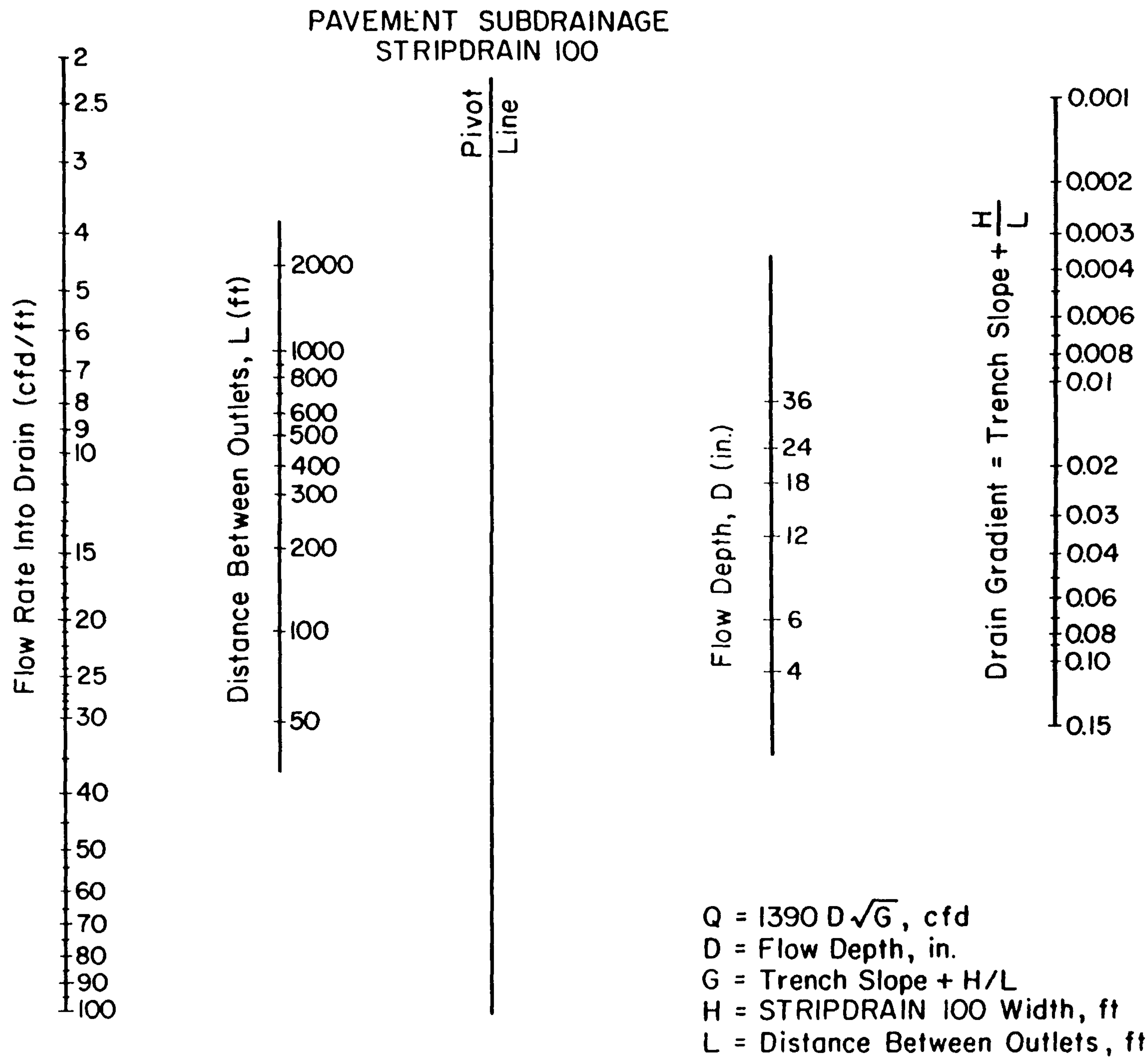


Figure 5.27 Typical Flow Nomograph for STRIPDRAIN 100.

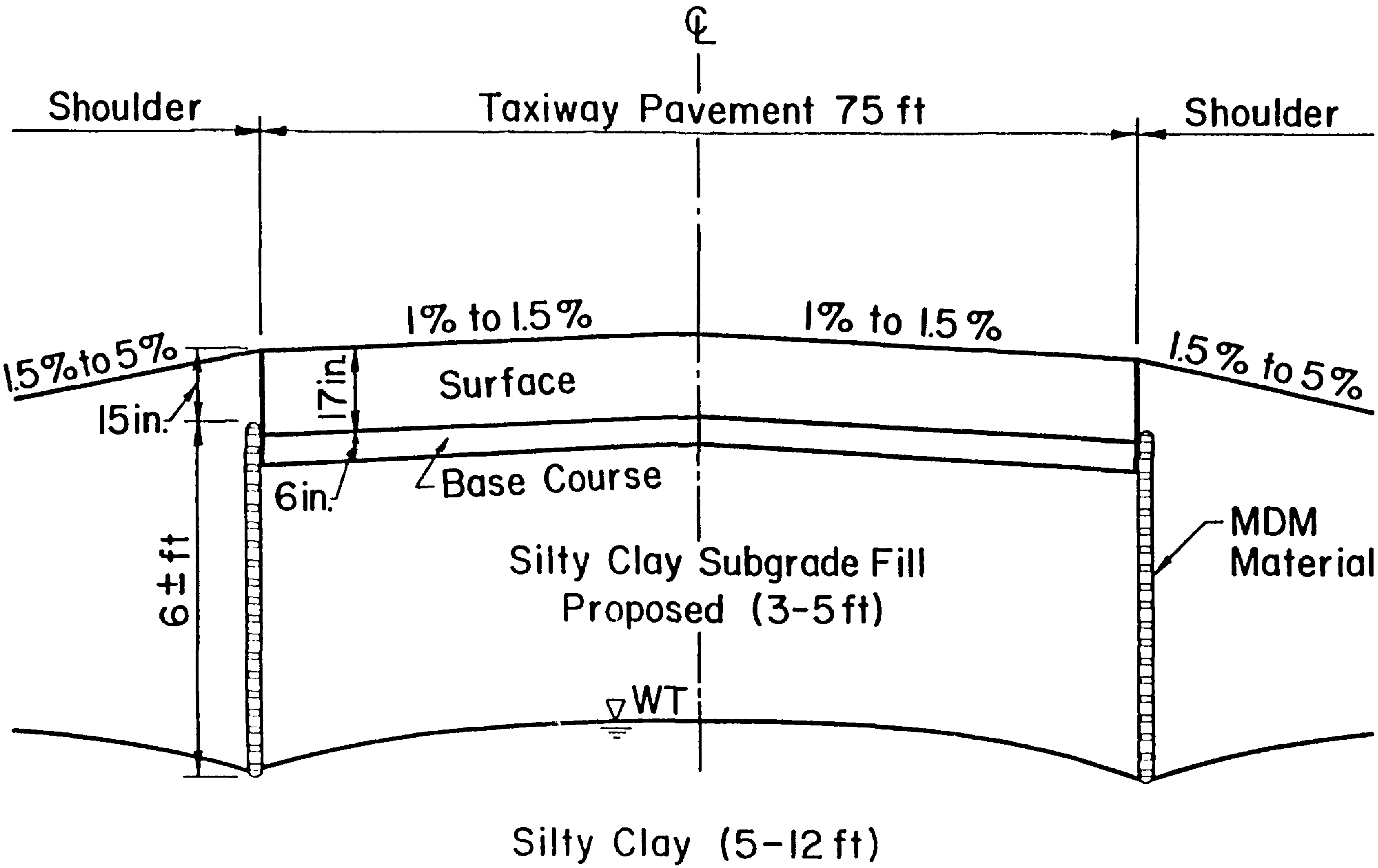


Figure 5.28 A PGS System which Provides Both Structural Pavement Drainage and Water Table Depth Control.

Chapter 6

CONSTRUCTION EQUIPMENT AND PROCEDURES FOR SUBSURFACE DRAINAGE INSTALLATION

6.1 Construction Equipment

6.1.1 General

Pavement subsurface drainage construction has been enhanced considerably over the last few years as a result of improved trenching equipment and better materials handling capability. With the development of the flexible plastic pipe and prefabricated geocomposite subdrainage (PGS) materials, subdrainage installation has become much more efficient and considerably less expensive.

6.1.2 Subsurface Drainage Trenchers

Considerable advancements have been made in the manufacture of trenching equipment for subsurface drainage installation. Figure 6.1 shows a small wheel trencher installing a geotextile wrapped flexible plastic pipe. Figures 6.2, 6.3, and 6.4 show a sequence of trencher operations in which a PGS material is being placed in a 4-in. wide trench. Figure 6.5 shows a large high-powered wheel trencher installing a PGS material. With the high powered wheel trenchers it is possible to cut through full depth asphalt concrete and reinforced portland cement concrete pavements. Installation rates of up to 9 miles per day have been achieved with large trenchers during placement of PGS systems in highway pavements.

Many of the trenchers used for subdrainage installation have laser units for grade control. These units provide the trenchers with the capability of operating off the pavement grade or independent of the pavement grade. Many of the trenchers can also be pivoted on their axle so that vertical trench cuts can be made even on pavements with a sloped cross section. Through the use of large trenchers it is possible to install pavement subsurface drainage at costs in the range of $2.00 to $4.00 - per ft.

6.1.3 Pipe Handling Equipment

With the development of flexible plastic pipe it became possible to deliver materials to the job site in rolls instead as individual sections. This capability should be considered as a major advancement in pavement subsurface drainage construction. Figure 6.6 shows a vertical reel feeding out flexible plastic pipe. This type of equipment can also be used to lay out the PGS material as shown in Figure 6.7. Figures 6.8 and 6.9 show two methods which can be used to feed out PGS materials from horizontal spindles. Many of the units constructed for hauling flexible pipe and PGS materials have built-in hydraulic controls to allow for easy pickup of new material rolls.

6.2 Construction Procedures

Numerous procedures have been developed for constructing improved subsurface drainage system for pavements. Figure 6.10 shows a section of portland cement stabilized open graded subbase on a roadway. Figure 6.11 shows placement of

an asphalt cement stabilized open graded subbase on an apron construction project at the University of Illinois Willard Airport.

Figure 6.12 shows installation of a PGS system in a full depth asphalt concrete pavement at Kewanee Airport in Illinois. A unique aspect of this installation was that a line of PGS material was placed on both sides of the runway centerline at a distance of 12.5 ft. Figure 6.13 shows the completed installation on the runway and the narrow trench which can be used with the PGS system as indicated by the asphalt plug. After about five years of service there has been no problems with settlement in the asphalt concrete plug placed in the drainage trench.

Figures 6.14, 6.15, and 6.16 show several different types of end connectors used to attach the PGS materials to circular pipes at Kewanee Airport. Figure 6.16 is an interconnection for transverse and longitudinal PGS systems in the Kewanee Airport runway. Most all PGS systems will be connected to the outlet by circular pipes.

6.3 Summary

This chapter shows that procedures are well advanced for installation and construction of pavement subsurface drainage systems. Modern trenchers and pipe distribution equipment are readily available and they can be used for fast, efficient, and economical installation of pavement subsurface drainage.

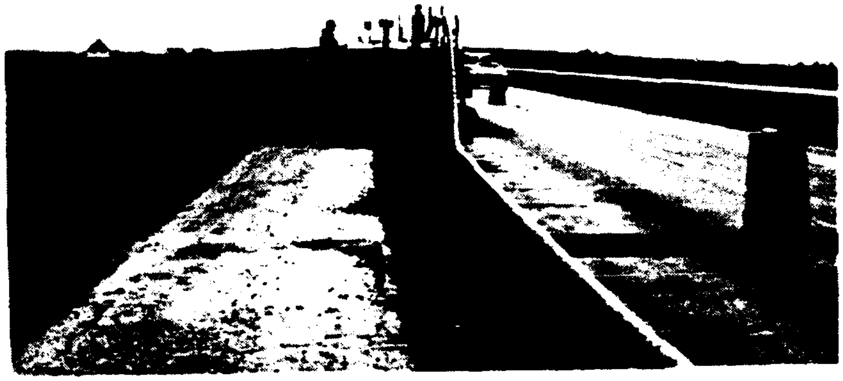


Figure 6.1 Small Wheel Trencher Placing Flexible Plastic Pipe.

Figure 6.2 Small Wheel Trencher Placing PGS Material.

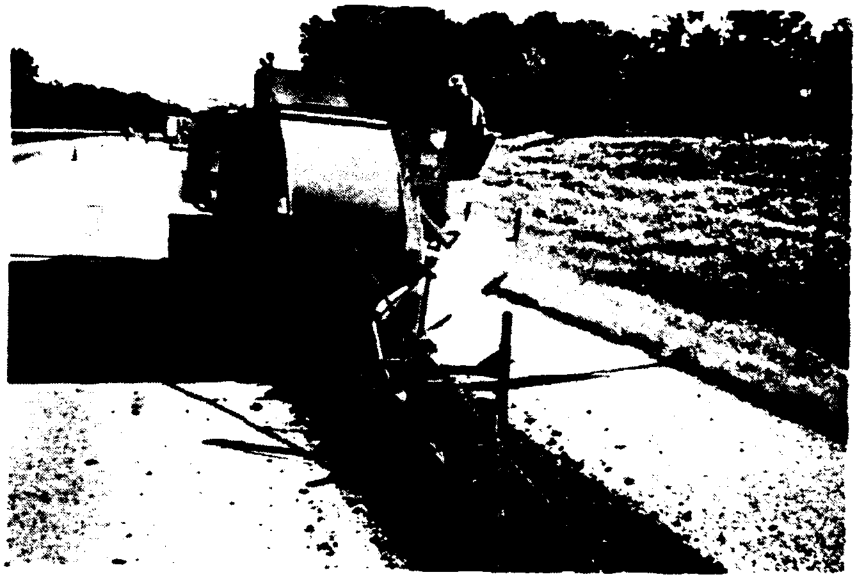


Figure 6.3 Trencher and PGS System Installation Boot.

Figure 6.4 Backfill and Compaction Phase of PGS System Installation.

Figure 6.5 Large High-Powered Trencher Installing a PGS Material.

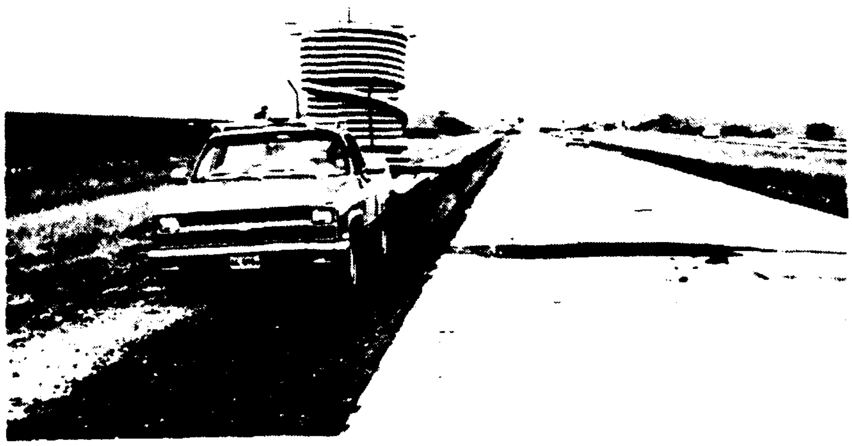


Figure 6.6 Vertical Distribution Reel for Flexible Pipe.

Figure 6.7 Vertical Distribution Reel for PGS Material.

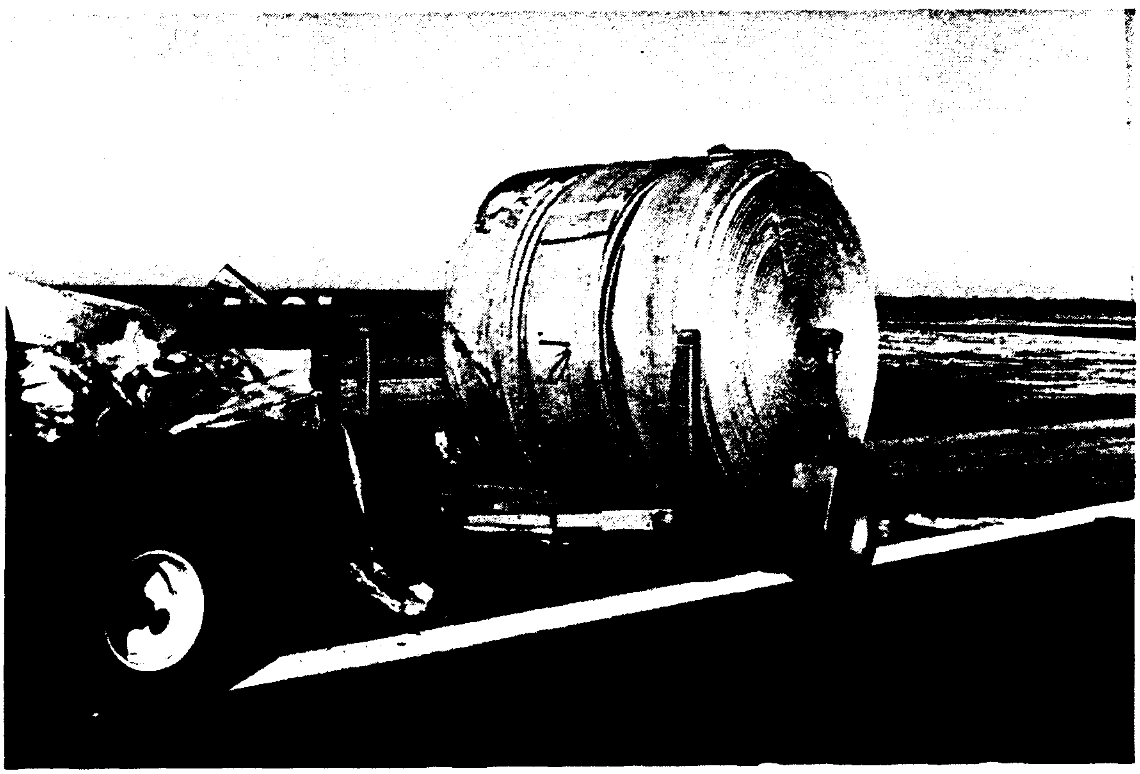


Figure 6.8 Small Horizontal Reel for Distributing PGS Material.

Figure 6.9 Distribution of PGS Material from a Special Truck Bed.

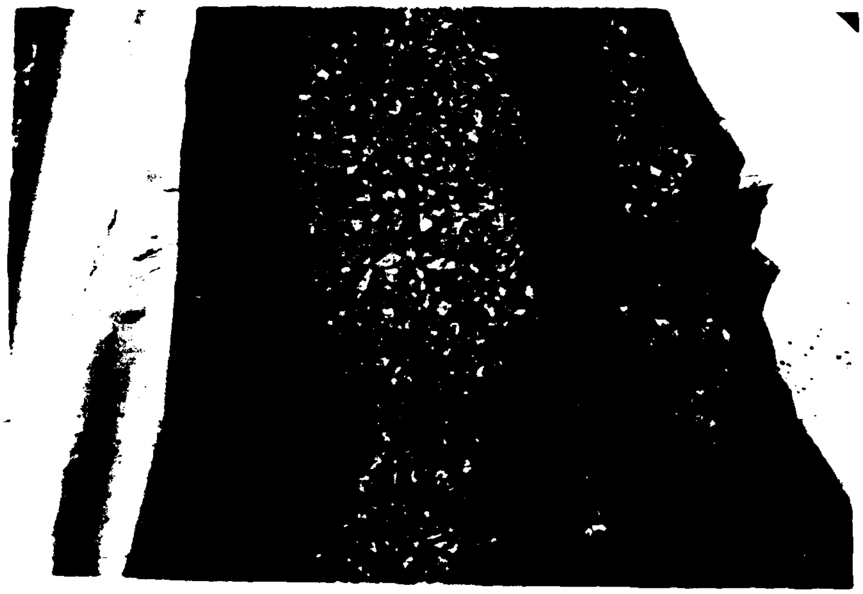


Figure 6.10 Portland Cement Stabilized Open Graded Subbase.

Figure 6.11 Asphalt Cement Stabilized Open Graded Subbase at Willard Airport.

Figure 6.12 Installation of PGS System on Runway at Kewanee Airport, Illinois.

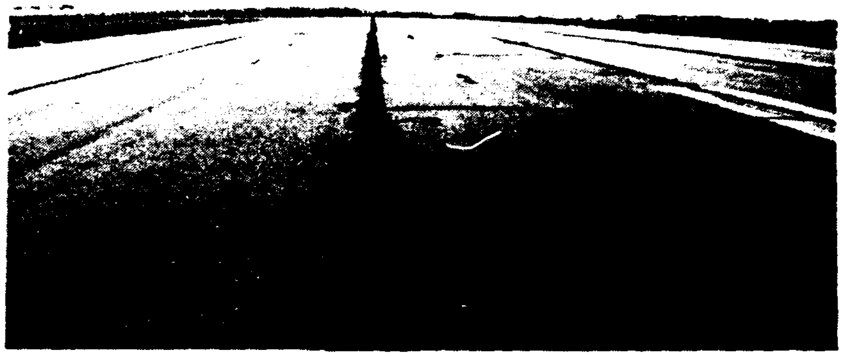


Figure 6.13 Completed PGS System Installation on the Kewanee Airport Runway.

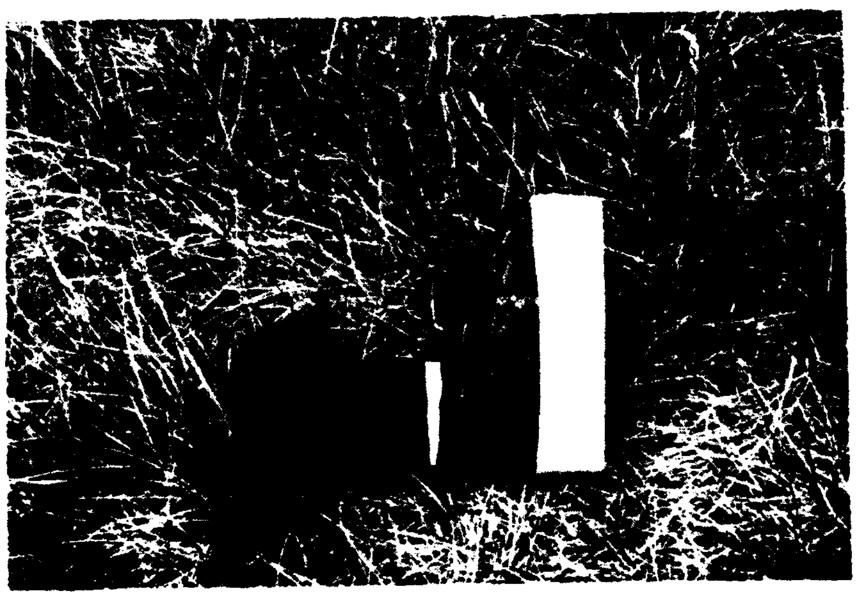


Figure 6.14 Endcap for PGS System with Circular Pipe Connector.

Figure 6.15 Interconnection of PGS Endcaps with Circular Pipe.

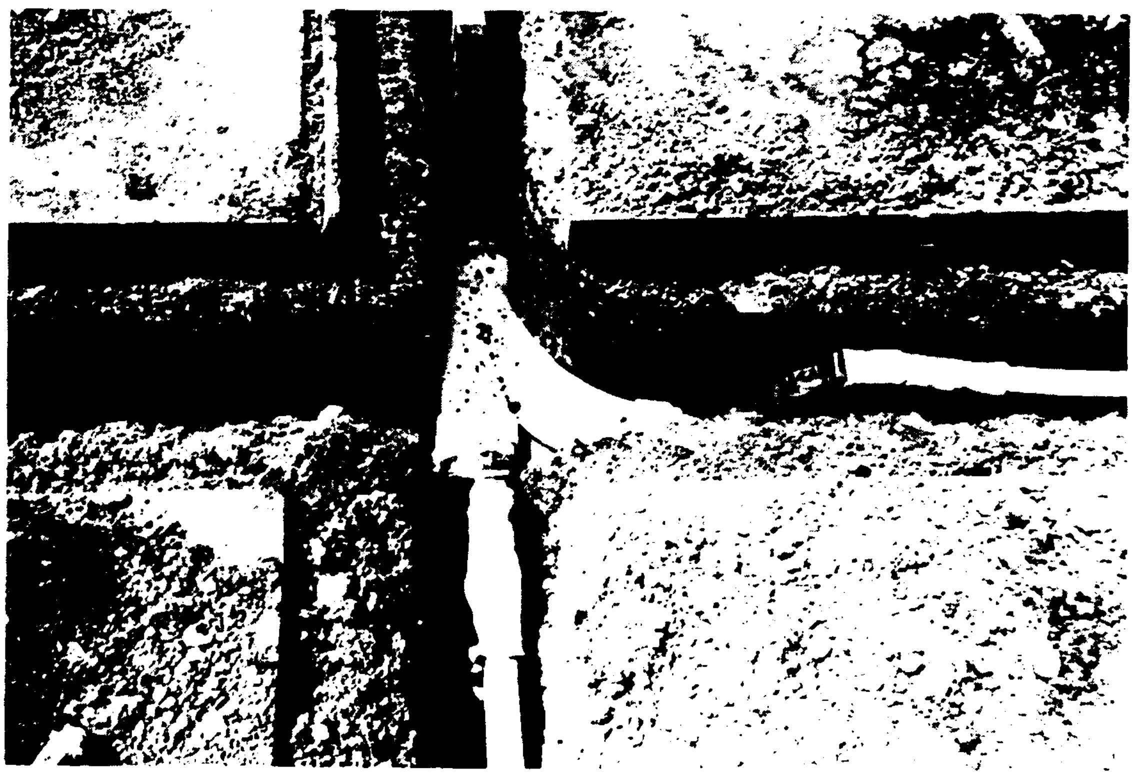


Figure 6.16 Interconnection for Transverse and Longitudinal PGS Systems in the Kewanee Airport Runway.

Chapter 7

PAVEMENT SUBSURFACE DRAINAGE MAINTENANCE AND EVALUATION

7.1 Subsurface Drainage Maintenance

Good pavement subsurface drainage performance starts with proper installation and thorough inspection during construction. However, after construction poorly maintained subsurface drainage can have detrimental influence on pavement performance. A blocked subdrain may provide a source of water to the pavement system. For this reason it is important to schedule maintenance of pavement subdrainage systems and determine if they are working properly.

Inefficiency in pavement subdrainage is normally caused by poor design or construction practices and clogging with soil, plant roots, or chemical deposits.

To insure that a subdrain is operating properly the following observations are recommended at periodic intervals:

1. Outflow observations to determine discharge rate.

2. Water table observations to determine whether the water table over the drain is lowered to drain shortly after rain stops.

3. Chemical observations to determine if chemical precipitates are present which will clog the drain.

In an effort to relieve blocked subsurface drainage systems and restore them to full efficiency cleaning and maintenance procedures are necessary. Figure 7.1 shows a high pressure cleaning unit for circular subdrainage pipe. Through the use of a special high pressure nozzle shown in Figure 7.2 it is possible to clean 500 ft to 600 ft of pipe. As shown in Figure 7.1, a high pressure pump which can produce up to 1000 psi pressure pumps water to the high pressure hose on the reel. The hose is fed off the reel by the propelling action of the nozzle shown in Figure 7.2. The nozzle has several angled jets at the rear which pushes it through the pipe and washes the sediments back towards the pipe opening. An electric rewind on the reel pulls the hose back onto the reel. Water should be pumped through the system during the rewind operation in order to wash materials from the pipe. In some cases a jet is installed in the nose of the nozzle to help clear a blocked pipe. Although a high pressure nozzle cannot be placed into the core of the PGS systems it is still possible to flush these systems with water pumped in through the outlets.

Drainage outlets should be checked often to see that they have not been damaged or blocked with grass and other debris. Checks should be made to insure that the rodent screens are in place. A periodic check during periods of rain will provide information relating to the operation of the pavement subsurface drainage system.

7.2 Subsurface Drainage Evaluation

A Pavement Condition Index (PCI) survey should be made at regular intervals to evaluate the pavement performance. Carpenter, Darter, and Dempsey (1) have described the various types of pavement distresses which are caused by moisture damage. Management of the surveys can be easily handled through a system such as Micro PAVER (2). Other types of evaluation procedures that can be used to determine subsurface drainage effectiveness include measurement of crack and joint faulting, pumping, rutting, and surface deflections.

The subsurface drainage system performance can be evaluated by measuring the response time and volume of the outflow during rainfall. Figure 7.3 shows a simple tipping bucket device for measuring outflow. An event recorder keeps a record of time and the number of times the tipping bucket empties. A rain gauge should be located near the outflow site for rainfall data. Outflow can also be measured by use of a metering flume and data logger. This type of equipment can operate for long periods in the field without attention. However the initial equipment costs can be high.

The internal condition of subsurface drainage pipe can be monitored by use of a small remote video camera which is pushed into the pipe. These units can be extended over a considerable distance into a pipe. The condition of the pipe is monitored on a T.V. screen.

The internal condition of the PGS system can be monitored by an optical borescope shown in Figure 7.4. Figure 7.5 shows an internal borescope view of an operating PGS material. A small pipe extending from the surface down through the top of the PGS material will provide easy access for the small barrel of the borescope.

7.3 Summary

Pavement subsurface drainage requires periodic maintenance checks for performance. Drainage outlets are especially vulnerable to blockage and should be checked often.

There are numerous procedures for evaluating subsurface drainage performance. Periodic outflow measurements should be conducted. Internal drainage condition can be determined by the use of remote video cameras and optical borescopes.

REFERENCES

1. Carpenter, S. H., Darter, M. I., and Dempsey, B. J., "A Pavement Accelerated Distress (MAD) Identification System, Users Manual-Volume 2," Report No. FHWA/RD-81/080, Federal Highway Administration, Washington, D.C., 1981.

2. Shahin, M. Y., Cation, K. A., and Broten, M. R., "Micro PAVER Concept and Development Airport Pavement Management System," DOT/FAA/PM-87-7, Federal Aviation Administration, Washington, D.C., 1987.

Figure 7.1 High Pressure Cleaning Unit for Pavement Subsurface Drainage Systems.

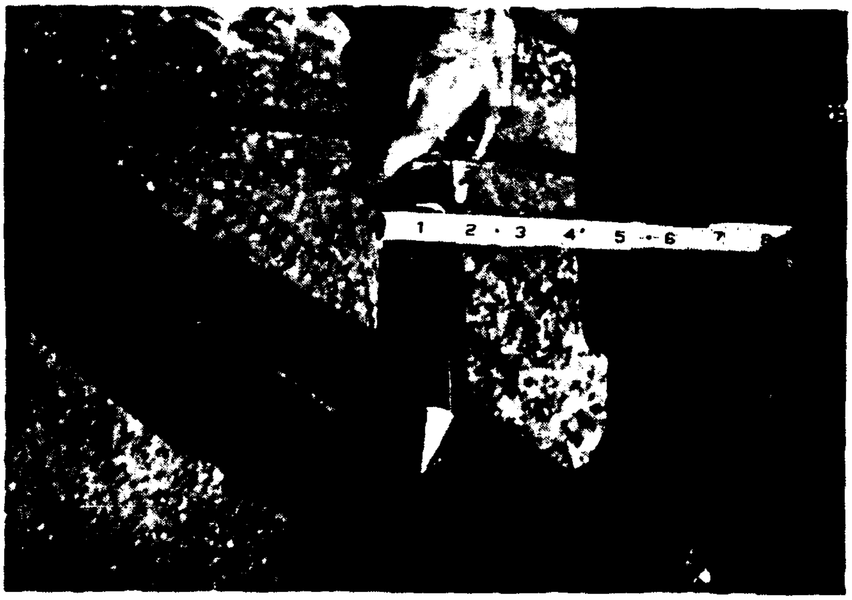


Figure 7.2 Propelling Nozzle for Cleaning Subsurface Drainage Systems.

Figure 7.3 Tipping Bucket Outflow Meter.

Figure 7.4 Borescope Observation of a PGS System.

Figure 7.5 Internal Borescope View of an Operational PGS System.

Chapter 8

SUMMARY AND RECOMMENDATIONS

8.1 Summary

This report provides comprehensive guidelines for the design, construction, and evaluation of airport pavement drainage. Procedures for considering climatic effects on airport drainage are described. Brief summaries of several climatic models which can be used to generate temperature and moisture conditions in pavements are presented.

A review of the FAA design procedures for airport surface drainage are presented in order to maintain comprehensive coverage of all aspects of drainage in a single report. Pavement surface drainage is discussed in terms of pavement grooving and the use of porous friction courses.

Pavement subsurface drainage is discussed in detail. Methods for determining the sources and quantity of water which enter the pavement are provided. Procedures for designing subbase drainage layers, blankets, and filter layers have been presented. Based on the sources and quantity of water which enters the pavement, methods for selecting and sizing the subdrainage collectors and outlets are discussed. Both the use of conventional circular pipe systems and prefabricated geocomposite subdrainage (PGS) systems are described.

The types of equipment and procedures for installation of pavement subsurface drainage are presented. The steps necessary for maintaining pavement subsurface drainage systems are discussed. Some of the methods for evaluating how well a subsurface drainage system is functioning are presented for information. The materials presented in Chapters 1 through 7 fulfill the objectives stated for this report.

8.2 Recommendations

The following recommendations are made for implementation and further studies of airport pavement drainage:

1. Detailed field studies are required to evaluate the performance of open graded subbase or drainage blanket materials now being used in airport pavements.

2. Both pipe drains and prefabricated geocomposite subdrainage (PGS) systems should perform well in airport pavements. The PGS system technology should be included in the FAA standards on pavement subsurface drainage.

3. Design nomographs similar to Figures 5.26 and 5.27 need to be developed for additional PGS systems which can meet airport drainage standards. Most PGS materials display their own unique structural and hydraulic properties and must be evaluated on product and manufacturer bases.

4. Innovative pavement drainage systems need to be studied. Combination drains which provide both structural pavement drainage and water table control should be considered.

5. Pavement retrofit with subdrainage systems placed in the structural section within the aircraft wander area need to be evaluated further. It may be possible to combine pavement surface drainage with the subdrainage system.

6. The various climatic programs (MAD, CMS, Integrated Climatic Model) and pavement subsurface drainage model programs (DAMP) need to be implemented for active use by engineers in the FAA.

APPENDIX A
PAVEMENT SUBSURFACE
DRAINAGE PROGRAM HSD3.BAS

```
1 KEY 1, "LIST ":SCREEN 0
10 'HIGHWAY SUBDRAINAGE DESIGN
20 'UNIVERSITY OF ILLINOIS
30 ' SUMMER 1987
50 ' VERSION 3G
60 KEY 6,"RESET"+CHR$(13)
70 ON KEY (6) GOSUB 10 :KEY (6) ON
100 'TITLE ***********************************************************************
110 CLS
120 PRINT
130 PRINT "                    HIGHWAY SUBDRAINAGE DESIGN"
140 PRINT "             DEVELOPED FROM U.S. DEPT OF TRANSPORATION"
150 PRINT "                       REPORT # FHWA-TS-80-224"
160 PRINT "                        UNIVERSITY OF ILLINOIS"
170 '     "                              VERSION 3G  "
180 PRINT "                    THOMAS V. MAY  BARRY J. DEMPSEY"
190 PRINT
200 'INTRODUCTION ****************************************************************
205 PRINT "GUIDELINES FOR USE OF PROGRAM TO COMPUTE NET INFLOW FOR DESIGN OF PAVEMENT      DRAINAGE.":PRINT
210 PRINT "THIS PROGRAM IS INTENDED TO BE A TOOL FOR USE WITH THE DESIGN MANUAL NOT AS A"
215 PRINT "REPLACEMENT FOR THE MANUAL.  THE USER WILL FIND IT NECESSARY TO HAVE A COPY"
220 PRINT "OF THE MANUAL, AS IT WILL CLARIFY THE TYPE OF PROBLEMS COVERED AND THE MEANING"
225 PRINT "OF DEMINSIONS CALLED FOR. ALSO THE MANUAL OFFERS ADVICE ON INTERPRETING THE "
230 PRINT "RESULTS WHICH IS NOT CONTAINED IN THE PROGRAM.  THIS PROGRAM CONTAINS MANY OF "
235 PRINT "THE CHARTS FROM CHAPTER 3,PAVEMENT DESIGN, IN FORMULA FORM.  THE FIGURE OR PAGE"
240 PRINT "NUMBER GIVEN IN THE COMMENTS TELLS YOU WHERE THE CORRESPONDING SECTION OF THE"
245 PRINT "MANUAL CAN BE FOUND."
250 PRINT
255 PRINT "IF AT ANY TIME YOU WISH TO RETURN TO THE BEGINNING OF THE SECTION YOU ARE "
260 PRINT "WORKING ON PRESS FUNCTION KEY 6 AND RETURN."
265 PRINT
270 PRINT " INPUTS: ALL VALUES SHOULD BE GIVEN IN THE UNITS SPECIFIED.
275 PRINT "         TO ANSWER A QUESTION GIVE THE LETTER IN () WHICH"
280 PRINT "         CORRESPONDS TO YOUR ANSWER.  ARE YOU READY TO GO ON (Y/N)?";
285 A$=INPUT$(1):IF A$="Y" OR A$="y" THEN 290:GOTO 10
290 '
295 IF A$="N" OR A$="n" GOTO 200:PRINT
299 QA=0:QV=0:QM=0:QI=0:QG=0
300 ' SELECTING TYPE OF DESIGN AND SECTIONS OF PROGRAM TO USE *****************
302 CLS
305 ON KEY(6) GOSUB 300 : KEY(6) ON
310 PRINT " DESIGN CATAGORIES"
320 PRINT " 1 COMPLETE DESIGN ALL FACTORS CONSIDERD"
330 PRINT " SPECIFIC SOURCE DESIGNS"
340 PRINT "  ***INFLOW***"
350 PRINT " 2 MELT WATER FROM ICE LENSES"
360 PRINT " 3 SURFACE INFILTRATION"
370 PRINT " 4 GRAVITY FLOW INTO CUTS"
380 PRINT " 5 ARTESIAN FLOW INTO CUTS"
390 PRINT "  ***OUT FLOW***"
400 PRINT " 6 UNDERLYING HIGH PERMEABILITY LAYER"
410 PRINT " 7 UNDERLYING WATER TABLE"
420 PRINT " 8 FLOW IN EMBANKMENT AND FOUNDATION "
425 PRINT  "  ***DRAIN DESIGN***"
430 PRINT " 9 DEPTH OF FLOW IN DRAINAGE BLANKET                                  OR REQUIRED PERMEABILITY OF D
```

```
435 PRINT " 0 EDGE DRAIN DESIGN"
440 PRINT
450 PRINT "ENTER THE NUMBER CORRESPONDING TO THE DESIGN REQUIREMENTS";
460 T$=INPUT$(1)
470 PRINT:PRINT
475 CLS:GOSUB 55000
480 PRINT"PRESS 1 TO SEE TYPICAL VALUES OF SOIL PERMEABILITY, STRIKE ANY OTHER KEY TO     CONTINUE";:P$=INPUT$(1)
485 CLS
490 IF P$="1" THEN GOSUB 40000
515 IF T$="1" THEN GOSUB 600
520 IF T$="2" THEN GOSUB 3000
530 IF T$="3" THEN GOSUB 1000
540 IF T$="4" THEN GOSUB 2000
550 IF T$="5" THEN GOSUB 8000
560 IF T$="6" THEN GOSUB 5000
570 IF T$="7" THEN GOSUB 4000
580 IF T$="8" THEN GOSUB 6000
590 IF T$="9" THEN GOSUB 9000
592 GOSUB 60000:GOTO 900
595 GOSUB 20000:GOTO 900
600 GOSUB 1000
602 CLS
605 ON KEY(6) GOSUB 600 : KEY(6) ON
610 PRINT " IS FROST ACTION TO BE CONSIDERD (Y/N)";:A$=INPUT$(1):PRINT
620 IF A$="N" OR A$="n" GOTO 640
630 GOSUB 3000
640 PRINT "IS THE SECTION A CUT (C) OR A FILL (F)";:B$=INPUT$(1):PRINT
650 IF B$="C" OR B$="c" GOTO 800
660 ' FILL
670 '
680 INPUT "IS THERE AN UNDERLYING LAYER OF HIGH PERMEABILITY (Y/N)";C$
690 IF C$="N" OR C$="n" GOTO 710
700 GOSUB 5000:GOTO 850
710 PRINT "IS THE ORIGINAL WATER TABLE SLOPED (S) OR FLAT (F)";:D$=INPUT$(1)
720 IF D$="S" OR D$="s" THEN GOSUB 4000
730 IF D$="F" OR D$="f" THEN GOSUB 6000
750 GOTO 850
800 ' CUT
810 PRINT "IS THERE GROUND WATER INFLOW ? NONE (N),GRAVITY (G), OR ARTESIAN (A)";:E$=INPUT$(1)
820 IF E$="G" OR E$="g" THEN GOSUB 2000
830 IF E$="A" OR E$="a" THEN GOSUB 8000
850 GOSUB 9000
860 RETURN
900 '
910 PRINT:PRINT "WOULD YOU LIKE TO EXAMEN ANOTHER SECTION (Y/N)";:S$=INPUT$(1)
920 IF S$="Y" OR S$="y" THEN GOTO 300
930 PRINT "WOULD YOU LIKE TO DESIGN AN EDGE DRAIN (Y/N)";:A$=INPUT$(1)
940 IF A$="Y" OR A$="y" THEN GOSUB 70000
950 END
980 KEY 6, "LPT1
990 END
992 '
994 '
996 '
```

```
1000 ' INFLOW FROM SURFACE INFILTRATION **************************************** 950
1002 ON KEY(6) GOSUB 1000 : KEY(6) ON
1005 'PAGES 62-63
1010 CLS
1020 PRINT "CALCULATION OF DESIGN SURFACE INFILTRATION RATE"
1030 INPUT "SPACING OF TRANSVERSE CRACKS OR JOINTS IN FEET (DEFAULT 40')";CS
1040 '
1050 IF CS>0 GOTO 1080
1060 CS=40
1080 INPUT "CRACK INFILTRATION RATE Ft3/DAY/Ft OF CRACK (DEFAULT 2.4)";IC
1100 IF IC>0 GOTO 1130
1110 IC=2.4
1130 INPUT "NUMBER OF TRAFFIC LANES";N
1150 NC=N+1
1160 INPUT "WIDTH OF GRANULAR BASE OR SUBBASE SUBJECTED TO INFILTRATION IN FEET";W
1180 INPUT "LENGTH OF CONTRIBUTING TRANSVERSE CRACKS OR JOINTS IN FEET";WC
1200 INPUT "COEFFICIENT OF PERMEABILITY THROUGH UNCRACKED PAVEMENT SURFACE Ft3/DAY/Ft2 ";KP
1220 QI=IC*(NC/W+WC/(W*CS))+KP
1250 PRINT "THE DESIGN INFLITRATION RATE =";QI;"FT3/DAY/FT2"
1260 PRINT:PRINT
1300 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
1500 RETURN
1510 '
1520 '
1530 '
2000 'FLOW INTO A HORIZONTAL DRAINAGE BLANKET IN A CUT ************************
2010 PRINT "GRAVITY FLOW INTO DRAINAGE SYSTEM"
2020 PRINT "DOES THIS DESIGN EMPLOY INTERCEPTOR DRAINS (Y/N)";:Q$=INPUT$(1)
2030 PRINT
2040 IF Q$="Y" OR Q$="y" THEN GOTO 10000
2050 ' FIGURE 36
2060 GOSUB 52000
2070 ON KEY(6) GOSUB 2005 : KEY(6) ON
2110 PRINT "FLOW INTO A HORIZONTAL DRAINAGE BLANKET IN A CUT."
2120 INPUT "PERMIABILITY K OF SOIL IN FT3/DAY/FT2";KG
2130 INPUT "WIDTH OF DRAINAGE BLANKET W IN FEET";WG
2140 INPUT "VERTICAL DISTANCE FROM DRAIN TO IMPERVIOUS LAYER IN FEET ";HG
2150 INPUT "VERTICAL DISTANCE FROM ORIGINAL WATER TABLE TO IMPERVIOUS LAYER IN FEET ";HB
2160 'CALCULATIONS
2170 'Li
2180 L1=3.8*(HB-HG)
2190 'Q
2200 IF WG/HG<1 GOTO 2250
2210 R=1:T=(WG/HG-1)*.25
2220 GOTO 2350
2250 T=0:R=1+2/(L1+.5*WG)/HG*(1-WG/HG)
2260 X=(L1+.5*WG)/HG
2270 '
2280 Y=.5*X*R-T
2300 '
2350 '
2360 X=(L1+.5*WG)/HG
2370 '
2380 Y=.5*X*R-T
2400 '
```

```
2410 Q1=.5*KG*(HB-HG)/Y
2420 QG=Q1/(.5*WG)
2440 PRINT "AN INFLOW OF ";QG;" FT3/DAY/FT2 WILL ENTER THE DRAINAGE BLANKET
2500 'FLOW INTO SIDES OF DRAINS
2510 PRINT "IN ADDITION TO THIS INFLOW THERE WILL ALSO BE A FLOW DIRECTLY INTO THE SIDE DRAINS. THIS FLOW MUST BE CONSIDERD
2520 '
2530 Q2=KG*(HB-HG)^2/(2*L1)
2540 PRINT "THE SIDE INFLOW WILL BE ";Q2;" FT3/DAY/FT2 FOR EACH SIDE."
2550 '
2580 PRINT:PRINT
2590 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
2600 RETURN
2700 '
2710 '
2720 '
3000 'INFLOW OF MELT WATER FROM ICE LENSES ************************************
3001 ON KEY(6) GOSUB 3000 : KEY(6) ON
3002 ' FIGURE 38
3005 PRINT "INFLOW OF MELT WATER FROM ICE LENSES"
3010 PRINT "WOULD YOU LIKE TO SEE A TABLE OF GUIDELINES ON FROST HEAVE (Y/N)?"; :H$=INPUT$(1):PRINT: IF H$="N" OR H$="n" TH
3015 'TABLE OF GUIDELINES FOR SELECTING HEAVE RATE
3020 PRINT "                    TABLE FOUR"
3030 PRINT:PRINT "   GUIDELINES FOR SELECTION OF HEAVE RATE OR FROST "
3040 PRINT
3050 PRINT" UNIFIED CLASSIFICATION      PERCENT    HEAVE RATE    FROST SUSCEPT."
3060 PRINT " SOIL TYPE         SYMBOL    <0.02 mm    mm/DAY       CLASSIFICATION"
3070 PRINT
3080 PRINT " GRAVELS AND         GP        0.4         3.0           MEDIUM"
3090 PRINT " SANDY GRAVELS"
3100 PRINT "                     GW       0.7-1.0    0.3-1.0       NEG. TO LOW"
3110 PRINT "                              1.0-1.5    1.0-3.5      LOW TO MEDIUM"
3120 PRINT "                              1.5-4.0    3.5-2.0         MEDIUM"
3130 PRINT
3140 PRINT " SILTY AND         GP-GM      2.0-3.0    1.0-3.0      LOW TO MEDIUM"
3150 PRINT " SANDY GRAVELS     GW-GM      3.0-7.0    3.0-4.5     MEDIUM TO HIGH"
3160 PRINT "                     GM"
3170 PRINT
3180 PRINT " CLAYEY AND        GW-GC      4.2        2.5             MEDIUM"
3190 PRINT " SILTY GRAVELS     GM-GC      15.0       5.0              HIGH"
3200 PRINT "                     GC     15.0-30.0  2.5-5.0     MEDIUM TO HIGH"
3210 PRINT
3220 PRINT " SANDS AND           SP       1.0-2.0    0.8            VERY LOW"
3230 PRINT " GRAVELY SANDS       SW       2.0        3.0              MEDIUM"
3240 PRINT
3250 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
3260 PRINT
3270 PRINT " SILTY AND         SP-SM      1.5-2.0    0.2-1.5       NEG. TO LOW"
3280 PRINT " GRAVELY SANDS     SW-SM      2.0-5.0    1.5-6.0       LOW TO HIGH"
3290 PRINT "                     SM       5.0-9.0    6.0-9.0   HIGH TO VERY HIGH"
3300 PRINT "                             9.0-22.0    9.0-5.5"
3310 PRINT
3320 PRINT " CLAYEY AND        SM-SC     9.5-35.0    5.0-7.0           HIGH"
3330 PRINT " SILTY SANDS         SC"
3340 PRINT
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3350 PRINT " SILTS AND      ML-OL       23.0-33.0   1.1-14.0  LOW TO VERY HIGH"
3360 PRINT " ORGANIC SILTS    ML        33.0-45.0  14.0-25.0         VERY HIGH"
3370 PRINT "                            45.0-65.0   25.0             VERY HIGH"
3380 PRINT
3390 PRINT " CLAYEY SILTS   ML-CL       60.0-75.0   13.0             VERY HIGH"
3400 PRINT
3410 PRINT " GRAVELY AND      CL        38.0-65.0    7.0-10.0  HIGH TO VERY HIGH"
3420 PRINT " SANDY CLAYS"
3430 PRINT
3440 PRINT " LEAN CLAYS       CL        65.0         5.0                 HIGH"
3450 PRINT "                CL-OL       30.0-70.0    4.0                 HIGH"
3460 PRINT
3470 PRINT " FAT CLAYS        CH        60.0         0.8             VERY LOW"
3500 ' SECTION PROPERTIES
3510 INPUT "HEAVE RATE IN mm/DAY";H2
3520 INPUT "PERMEABILITY OF SOIL IN FEET/DAY";KM
3530 INPUT "UNIT WEIGHT OF PAVEMENT IN LBS/FT3";PW
3540 INPUT "PAVEMENT THICKNESS IN INCHES";PT
3550 INPUT "UNIT WEIGHT OF SUBBASE IN LBS/FT3";SW
3560 INPUT "SUBBASE THICKNESS IN INCHES ";ST
3570 '
3580 S=PW*PT/12+SW*ST/12
3590 '
3600 X=(S/100)^.5*(1/7*H2^(2/3)*(1-.3/7*H2^(2/3))+(1/1333)*H2^2+.003/(H2^2))
3610 '
3620 QM=X*(KM^.5)
3630 '
3640 PRINT "INFLOW FROM MELTING ICE LENSES =";QM;" FT3/DAY/FT2"
3650 PRINT:PRINT
3700 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
3800 RETURN
3810 '
3820 '
3830 '
4000 ' ESTIMATING VERTICAL OUTFLOW FROM PAVEMENT STRUCTURE SECTION THROUGH SUBGRADE    SOIL TO A SLOPING UNDERLYING WATER T
4005 ON KEY(6) GOSUB 4000 : KEY(6) ON
4010 ' FIGURE 43
4015 GOSUB 51000
4020 PRINT "ESTIMATING VERTICAL OUTFLOW FROM PAVEMENT STRUCTURE SECTION THROUGH SUBGRADE    SOIL TO A SLOPING UNDERLYING WA
4025 PRINT
4030 ' INPUTS
4040 INPUT "THE WIDTH OF THE PAVEMENT STRUCTURE IN FEET";WS
4050 INPUT "THE DEPTH TO THE IMPERVIOUS LAYER IN FEET";DS
4060 INPUT "THE ORIGINAL THICKNESS OF THE WATER TABLE OVER THE IMPERVIOUS LAYER IN FEET";HS
4070 INPUT "THE SLOPE OF THE IMPERVIOUS LAYER (FEET RISE/FOOT RUN) ";SS
4080 INPUT "THE PERMEABILITY OF THE SOIL IN FEET/DAY ";KS
4090 '
4100 J=HS/DS
4110 '
4120 X=WS/DS
4130 '
4140 Y=(1-J)/X
4150 '
4160 'OUTFLOW
4170 QS=Y*KS*SS
```

```
4180 '
4190 PRINT "OUTFLOW TO UNDERLYING WATER TABLE IS ";QS;" FT3/DAY/FT2"
4200 PRINT:PRINT
4300 PRINT "PRESS FUNCTION KEY 5 TO CONTINUE.":STOP
4500 RETURN
4800 PRINT
4810 '
4820 '
4830 '
5000 'ESTIMATING VERTICAL OUTFLOW TO A HIGH PEREABILITY LAYER *****************
5005 ON KEY(6) GOSUB 5000 : KEY(6) ON
5010 'FIGURE 44
5015 GOSUB 56000
5020 PRINT "ESTIMATING VERTICAL OUTFLOW TO A HIGH PERMEABILITY LAYER."
5030 '
5040 INPUT "WIDTH OF THE PAVEMENT STRUCTURE (FT)";WP
5050 INPUT "DISTANCE FROM THE PAVEMENT TO THE HIGH PERMEABILITY LAYER (FT)";DP
5060 INPUT "ORIGINAL DISTANCE FROM THE WATER TABLE TO THE HIGH PERMEABILITY LAYER (FT)";HP
5070 INPUT "PERMEABILITY OF THE SOIL (FT/DAY)";KP
5080 '
5090 '
5100 J=WP/DP
5110 '
5120 X=HP/DP
5130 '
5140 Y=(1-X^((1/J)+.9*J))
5150 '
5160 QP=KP*Y
5170 '
5180 PRINT "OUTFLOW TO UNDERLYING HIGH PERMEABILITY LAYER ";QP;" FT3/DAY/FT2"
5190 PRINT:PRINT
5200 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
5500 RETURN
5510 '
5520 '
5530 '
6000 ' ESTIMATING VERTICAL OUTFLOW FROM A PAVEMENT STRUCTURE SECTION THROUGH EMBANKMENT AND FOUNDATION SOIL ***************
6005 ON KEY(6) GOSUB 6000 : KEY(6) ON
6010 ' FIGURE 45
6015 GOSUB 57000
6020 '
6040 PRINT "ESTIMATING VERTICAL OUTFLOW FROM A PAVEMENT SECTION THROUGH EMBANKMENT AND FOUNDATION SOIL ."
6050 INPUT "THE WIDTH OF THE PAVEMENT STRUCTURE (IF THE PAVEMENT IS ASYMMETRICAL SUCH THAT  ALL THE FLOW IS OUT ONE SIDE EN
6060 INPUT "THE HORIZONTAL DISTANCE FROM THE EDGE OF THE PAVEMENT TO THE TOE OF THE SLOPE IN FEET ";LV
6070 INPUT "THE HEIGHT OF THE EMBANKMENT IN FEET";HV
6080 INPUT "THE DEPTH TO THE IMPERVIOUS LAYER BELOW THE PAVEMENT IN FEET";DV
6090 INPUT "THE PERMEABILITY OF THE SOIL IN FEET/DAY";KV
6100 '
6110 '
6120 C=(1-.75*(HV/DV))
6130 Y=HV/WV
6140 J=LV/HV
6150 IF Y <1 GOTO 6180
6160 R=1/(600*Y)
6170 GOTO 6190
```

```
6180 R=0
6190 IF Y > .5 GOTO 6220
6200 G=.46*Y
6210 GOTO 6260
6220 IF Y > 1.3 GOTO 6250
6230 G=.23
6240 GOTO 6260
6250 G=.23-(Y-1.3)*.18
6260 X=((Y/1.14)^(1/1.7)*(1/1.6)-R+G*HV/LV)
6270 '
6280 QV=X*KV*C
6300 PRINT "OUTFLOW FROM PAVEMENT SECTION THROUGH EMBANKMENT AND FOUNDATION SOIL";QV
6310 PRINT:PRINT
6400 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
6500 RETURN
6510 '
6520 '
6530 '
8000 'ARTESIAN INFLOW IN A CUT ************************************************
8002 ON KEY(6) GOSUB 8000 : KEY(6) ON
8005 ' PAGE 68
8007 GOSUB 53000
8010 PRINT "FLOW INTO CUT CAUSED BY ARTESIAN PRESSURE"
8020 INPUT "PERMIABILITY IN FEET/DAY";KA
8030 INPUT "THE EXCESS ARTESIAN HEAD IN FEET ";DH
8040 INPUT "THE THICKNESS OF SUBGRADE SOIL BETWEEN ARTESIAN AQUIFER AND DRAINAGE LAYER IN   FEET";HA
8050 '
8060 QA=KA*DH/HA
8100 PRINT "ARTESIAN FLOW INTO CUT IS ";QA;" FT3/DAY/FT2"
8110 PRINT:PRINT
8400 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
8500 RETURN
8510 '
8520 '
8530 '
9000 'MAXIUM DEPTH OF FLOW CAUSED BY STEADY INFLOW ****************************
9002 CLS
9005 ON KEY(6) GOSUB 9000 : KEY(6) ON
9010 '
9020 PRINT "DO YOU WISH TO FIND THE MAXIMUM DEPTH OF FLOW (D), OR THE REQUIRED PERMEABILITY (K)";: Y$=INPUT$(1): PRINT
9025 'NET INFLOW CALCULATED THUS FAR IN THE ANALYSIS
9027 NI=QI+QM+QA+QG-QV-QS-QP
9028 PRINT "THE CALCULATED INFLOW THUS FAR IS ";NI;" Ft3/Day/Ft."
9030 IF Y$="K" OR Y$="k" GOTO 9500
9110 ' ESTIMATING MAXIUM DEPTH OF FLOW CAUSED BY STEADY INFLOW
9120 ' DATA INPUTS
9140 INPUT "THE COEFFICIENT OF PERMEABILITY IN FEET/DAY OF THE DRAIN ";KN
9150 INPUT "THE DESIGN INFLOW RATE IN FT3/DAY/FT2";QN
9160 INPUT "THE SLOPE OF THE IMPERVIOUS LAYER";SN
9170 INPUT "THE LENGTH OF THE FLOW PATH";LN
9180 P=QN/KN
9190 R=1/P^.5-22*10^6*P^6
9210 D=R+1/R
9230 X=8*SN*((D^.5)-2+1/D+(D^3)/(3*(10^5)))*D+D
9240 HN=LN/X
```

```
9250 PRINT"ESTIMATED DEPTH OF FLOW IN DRAINAGE BLANKET IS ";HN;" FEET."
9400 GOTO 9600
9500 '
9510 INPUT "THE DESIGN INFLOW RATE Ft3/DAY/Ft2";QN
9520 INPUT "THE SLOPE OF THE DRAINAGE LAYER";SN
9530 INPUT "THE LENGTH OF THE FLOW PATH feet";LN
9540 INPUT "THE DEPTH OF FLOW IN DRAINAGE LAYER feet";HN
9545 IF LN =0 OR HN=0 THEN 9585
9550 X=LN/HN
9560 Y=(1+1.1*X*SN)*(1/X^2-1/X^5)
9570 KN=QN/Y
9580 PRINT "REQUIRED COEFFICIENT OF PERMEABILITY APPROX. ";KN
9582 GOTO 9590
9585 PRINT "THESE VALUES ARE IMPOSSIBLE PLEASE SELECT NEW VALUES.":GOTO 9500
9590 PRINT:PRINT
9600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
9800 RETURN
9810 '
9820 '
9830 '
10000 'LONGITUDINAL INTERCEPTOR DRAINS*******************************************
10002 CLS
10005 ON KEY(6) GOSUB 10000 : KEY(6) ON
10010 PRINT "IS THIS DESIGN FOR A SLOPE CUT OR A SYMMETRICAL DRAINAGE SYSTEM (C/S)";
10020 S$=INPUT$(1)
10030 PRINT
10040 IF S$="S" OR S$="s" GOTO 10500
10047 PRINT
10050 GOSUB 52000
10060 INPUT "PERMIABILITY K OF SOIL IN FT3/DAY/FT2";KD
10070 INPUT "VERTICAL DISTANCE FROM BASE OF DRAIN TO IMPERVIOUS LAYER IN FEET";HD
10080 INPUT "VERTICAL DISTANCE FROM BASE OF PAVEMENT STRUCTURE TO IMPERVIOUS LAYER IN FEET";HD3
10090 INPUT "VERTICAL DISTANCE FROM ORGINAL WATER TABLE TO IMPERVIOUS LAYER IN FEET";HD1
10100 INPUT "SLOPE OF ORIGINAL WATER TABLE AND IMPERVIOUS LAYER";SD
10110 '
10200 ' CALCULATIONS FOR EQ 28,29,30
10210 L=3.8*(HD1-HD)
10220 '
10230 Z=HD1*10
10240 J=SD*L+(HD1-HD)
10250 '
10260 IF J<Z*LOG((Z-HD)/(Z-HD1)) GOTO 10
10270 Z=Z-.05*HD1 :GOTO 10260
10300 QD=KD*SD*(Z-HD)
10310 PRINT "FLOW INTO LONGITUDINAL INTERCEPTOR DRAIN IS "; QD;" FT3/DAY/FT."
10400 RETURN
10500 'SYMMETRICAL DRAINS
10510 GOSUB 54000
10520 PRINT " NOTE: THE GEOMETRY OF THE PAVEMENT IN QUESTION MUST BE SUCH THAT THE DRAINS ACT AS INTERCEPTOR DRAINS."
10530 INPUT "PERMIABILITY K OF SOIL IN FT3/DAY/FT2";KD
10540 INPUT "VERTICAL DISTANCE FROM BASE OF DRAIN TO IMPERVIOUS LAYER IN FEET";HD
10550 INPUT "VERTICAL DISTANCE FROM BASE OF PAVEMENT STRUCTURE TO IMPERVIOUS LAYER IN FEET";HD3
10560 INPUT "VERTICAL DISTANCE FROM ORGINAL WATER TABLE TO IMPERVIOUS LAYER IN FEET";HD1
10570 INPUT "WIDTH OF PAVEMENT STRUCTURE IN FEET";WD
10580 INPUT "WIDTH OF DRAIN IN FEET ";BD1
```

```
10590 BD=BD1/2
10600 ' CALCULATIONS
10610 IF BD/HD>.25 GOTO 10650
10620 R=0
10630 T=1/(SQR(BD/HD)-2)*.17-1.5*(BD/HD-.25)
10640 GOTO 10670
10650 T=0
10660 R=(BD/HD-.25)
10670 X=3.8*(HD1-HD)/HD
10680 Y=X+.1-R+T
10690 QD=(KD*(HD1-HD)^2)/(2*(3.8*(HD1-HD)-BD))+KD*(HD1-HD)/Y
10710 ' HEIGHT OF FREE WATER SURFACE BETWEEN SYMMETRICAL UNDERDRAINS
10720 QD2=KD*(HD1-HD)/Y
10740 IF WD/HD>.5 THEN J=.5 ELSE J=WD/HD
10750 Y=.3-.43*BD/HD-.5+J+SQR(1/(100*BD/HD))
10760 HD2=HD+Y*QD2/KD
10770 PRINT "FLOW INTO EACH SIDE DRAIN IS ";QD;"FT3/DAY/FT."
10780 PRINT "MAXIMUM HEIGHT OF FREE WATER SURFACE BETWEEN SYMMETRICAL UNDERDRAINS IS ";HD2;" FEET."
10785 IF HD2<HD3 THEN GOTO 10800
10790 PRINT "WARNING THE WATER TABLE INTERSECTS THE PAVEMENT STRUCTURE USE DEEPER DRAINS."
10795 GOTO 10000
10800 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
10900 RETURN
10910 '
10920 '
10930 '
20000 'RESULTS*****************************************************************
20005 ON KEY(6) GOSUB 20000 : KEY(6) ON
20010 CLS:PRINT " ######### RESULTS OF HIGHWAY SUBDRAINAGE DESIGN #########"
20020 PRINT
20030 PRINT "THE NET INFLOW (INTO STRUCTURE OF PAVEMENT ) FOR THIS PAVEMENT =";QI+QM+QA+QG-QV-QS-QP;" FT3/DAY/FT2"
20040 PRINT
20050 '
20060 IF HN=0 AND KN=0 GOTO 20080
20070 PRINT "ESTIMATED DEPTH OF FLOW IN A DRAINAGE LAYER WITH A COEFFICENT OF PERMEABILITY OF ";KN;" FEET/DAY IS ";HN;" FEE
20080 ' INFLITRATION
20090 IF QI=0 GOTO 20180
20100 PRINT "INFLOW FROM SURFACE INFLITRATION =";QI;" FT3/DAY/FT2"
20110 PRINT "SPACING OF TRANSVERSE CRACKS OR JOINT IN FEET";CS
20120 PRINT "LENGTH OF CONTRIBUTING TRANSVERSE CRACKS OR JOINTS IN FEET ";WC
20130 PRINT "CRACK INFILTRATION RATE FT3/DAY/FT OF CRACK ";IC
20140 PRINT "NUMBER OF TRAFFIC LANES ";N
20150 PRINT "WIDTH OF GRANULAR BASE OR SUBBASE SUBJECTED TO INFILTRATION ";W;"FEET"
20160 PRINT "COEFFICIENT OF PERMEABILITY THROUGH UNCRACKED PAVEMENT SURFACE FT/DAY ";KP
20170 PRINT:PRINT
20180 '
20190 IF QM=0 GOTO 20280
20200 PRINT "INFLOW FROM ICE LENSES MELT WATER ";QM;" FT3/DAY/FT2"
20210 PRINT "HEAVE RATE IN mm/DAY";H2
20220 PRINT "PERMEABILITY OF SOIL IN FEET/DAY ";KM
20230 PRINT "UNIT WEIGHT OF PAVEMENT IN LBS/FT3 ";PW
20240 PRINT "PAVEMENT THICKNESS IN INCHES ";PT
20250 PRINT "UNIT WEIGHT OF SUBBASE IN LBS/FT3 ";SW
20260 PRINT "SUBBASE THICKNESS IN INCHES ";ST
20270 PRINT:PRINT
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20280 '
20290 IF QV=0 GOTO 20370
20300 PRINT "VERTICAL OUTFLOW THROUGH EMBANKMENT AND FOUNDATION SOIL ";QV;"FT3/DAY/FT2"
20310 PRINT "WIDTH OF THE PAVEMENT STRUCTURE ";WV
20320 PRINT "HORIZONTAL DISTANCE FROM EDGE OF PAVEMENT TO TOE OF SLOPE";LV
20330 PRINT "HEIGHT OF THE EMBANKMENT IN FEET ";HV
20340 PRINT "DEPTH TO IMPERVIOUS LAYER ";DV
20350 PRINT "PERMEABILITY OF THE SUBGRADE SOIL ";KV
20360 PRINT:PRINT
20370 '
20380 IF QP=0 GOTO 20450
20390 PRINT "OUTFLOW TO UNDERLYING HIGH PERMEABILITY LAYER IS ";QP;" FT3/DAY/FT2"
20400 PRINT "WIDTH OF PAVEMENT STRUCTURE ";WP;" FEET."
20410 PRINT "DISTANCE FROM THE PAVEMENT TO THE HIGH PERMEABILITY LAYER ";DP;"FEET."
20420 PRINT "ORIGINAL DISTANCE FROM WATER TABLE TO HIGH PERMEABILITY LAYER ";HP;" FEET."
20430 PRINT "PERMEABILITY OF THE SOIL ";KP;" FEET/DAY."
20440 PRINT:PRINT
20450 '
20460 IF QS=0 GOTO 20540
20470 PRINT "OUTFLOW TO UNDERLYING WATER TABLE IS ";QS;" FT3/DAY/FT2."
20480 PRINT "WIDTH OF PAVEMENT STRUCTURE ";WS;" FEET."
20490 PRINT "DEPTH TO IMPERVIOUS LAYER ";DS;" FEET."
20500 PRINT "ORIGINAL THICKNESS OF THE WATER TABLE OVER THE IMPERVIOUS LAYER ";HS;" FEET."
20510 PRINT "SLOPE OF THE IMPERVIOUS LAYER (FEET RISE/FOOT RUN) ";SS
20520 PRINT "PERMEABILITY OF THE SOIL ";KS; " FEET/DAY."
20530 PRINT:PRINT
20540 '
20550 IF QA=0 GOTO 20610
20560 PRINT "ARTESIAN INFLOW  ";QA;" FT3/DAY/FT2"
20570 PRINT "PERMEABILITY OF SUBGRADE SOIL";KA;"Ft/DAY"
20580 PRINT "EXCESS ARTESIAN HEAD ";DH;"FEET"
20590 PRINT "THICKNESS OF SUBGRADE SOIL BETWEEN ARTESIAN AQUIFER AND DRAINAGE LAYER ";HA;"FEET"
20600 PRINT:PRINT
20610 '
20620 IF QG=0 GOTO 20690
20630 PRINT "FLOW INTO CUT FROM GRAVITY IS ";QG;" FT3/DAY/FT2"
20640 PRINT "PERMEABILITY IN FT/DAY ";KG
20650 PRINT "WIDTH OF DRAINAGE BLANKET IN FEET ";WG
20660 PRINT "VERTICAL DISTANCE FROM DRAIN TO IMPERVIOUS LAYER IN FEET ";HG
20670 PRINT "VERTICAL DISTANCE FROM ORIGINAL WATER TABLE TO IMPERVIOUS LAYER IN FEET ";HB
20680 PRINT "AN ADDITIONAL";Q2;"FT3/DAY/FT WILL FLOW DIRECTLY INTO THE SIDE OF THE DRAIN.":PRINT
20690 '
20780 '
20810 'LONGITUDINAL INTERCEPTOR DRAINS
20820 IF QD=0 GOTO 20900
20825 PRINT "FLOW INTO LONGITUDINAL INTERCEPTOR DRAIN IS ";QD;" FT3/DAY/FT."
20830 PRINT "PERMEABILITY OF SOIL IN FEET/DAY ";KD
20840 PRINT "VERTICAL DISTANCE FROM ORIGINAL WATER TABLE TO IMPERVIOUS LAYER IN FEET ";HD1
20850 PRINT "VERTICAL DISTANCE FROM BASE OF DRAIN TO IMPERVIOUS LAYER IN FEET ";HD
20860 IF BD=0 GOTO 20890
20870 PRINT "WIDTH OF PAVEMENT STRUCTURE IN FEET ";WD
20875 PRINT "WIDTH OF DRAIN IN FEET ";BD1
20880 PRINT "MAX. HEIGHT OF WATER BETWEEN DRAINS IS ";HD2;" FEET.":GOTO 20895
20890 PRINT "SLOPE OF ORIGINAL WATER TABLE ";SD
20900 PRINT :PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
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20910 PRINT
21900 PRINT "WOULD YOU LIKE A HARD COPY OF THESE RESULTS (Y/N)?";
21905 P$=INPUT$(1)
21910 IF P$="Y" OR P$="y" THEN GOSUB 22000
21950 RETURN
21960 '
21970 '
21980 '
22000 ' HARD COPY OF RESULTS **************************************************
22010 LPRINT
22020 LPRINT "THE NET INFLOW (INTO STRUCTURE OF PAVEMENT ) FOR THIS PAVEMENT =";QI+QM+QA+QG-QV-QS-QP;" FT3/DAY/FT2"
22030 LPRINT
22040 IF KN=0 AND HN=0 THEN GOTO 22060
22050 LPRINT "ESTIMATED DEPTH OF FLOW IN A DRAINAGE LAYER WITH A COEFFICENT OF PERMEABILITY OF ";KN;" IS ";HN;" FEET."
22060 ' INFLITRATION
22070 IF QI=0 GOTO 22160
22080 LPRINT "INFLOW FROM SURFACE INFLITRATION =";QI;" FT3/DAY/FT2"
22090 LPRINT "SPACING OF TRANSVERSE CRACKS OR JOINT IN FEET";CS
22100 LPRINT "LENGTH OF CONTRIBUTING TRANSVERSE CRACKS OR JOINTS IN FEET ";WC
22110 LPRINT "CRACK INFILTRATION RATE FT3/DAY/FT OF CRACK ";IC
22120 LPRINT "NUMBER OF TRAFFIC LANES ";N
22130 LPRINT "WIDTH OF GRANULAR BASE OR SUBBASE SUBJECTED TO INFILTRATION ";W;"FEET"
22140 LPRINT "COEFFICIENT OF PERMEABILITY THROUGH UNCRACKED PAVEMENT SURFACE FT/DAY ";KP
22150 LPRINT
22160 '
22170 IF QM=0 GOTO 22250
22180 LPRINT "INFLOW FROM ICE LENSES MELT WATER ";QM;" FT3/DAY/FT2"
22190 LPRINT "HEAVE RATE IN mm/DAY";H2
22200 LPRINT "PERMEABILITY OF SOIL IN FEET/DAY ";KM
22210 LPRINT "UNIT WEIGHT OF PAVEMENT IN LBS/FT3 ";PW
22220 LPRINT "PAVEMENT THICKNESS IN INCHES ";PT
22230 LPRINT "UNIT WEIGHT OF SUBBASE IN LBS/FT3 ";SW
22240 LPRINT "SUBBASE THICKNESS IN INCHES ";ST
22250 '
22260 IF QV=0 GOTO 22330
22270 LPRINT "VERTICAL OUTFLOW THROUGH EMBANKMENT AND FOUNDATION SOIL ";QV;"FT3/DAY/FT2"
22280 LPRINT "WIDTH OF THE PAVEMENT STRUCTURE ";WV
22290 LPRINT "HORIZONTAL DISTANCE FROM EDGE OF PAVEMENT TO TOE OF SLOPE";LV
22300 LPRINT "HEIGHT OF THE EMBANKMENT IN FEET ";HV
22310 LPRINT "DEPTH TO IMPERVIOUS LAYER ";DV
22320 LPRINT "PERMEABILITY OF THE SUBGRADE SOIL ";KV
22330 '
22340 IF QP=0 GOTO 22400
22350 LPRINT "OUTFLOW TO A HIGH PERMEABILITY LAYER ";QP;" FT3/DAY/FT2."
22360 LPRINT "PERMEABILITY OF SUBGRADE SOIL IN FEET/DAY ";KP
22370 LPRINT "WIDTH OF THE PAVEMENT STRUCTURE IS";WP;" FEET."
22380 LPRINT "DISTANCE FROM THE PAVEMENT TO THE HIGH PERMEABILITY LAYER ";DP;" FEET"
22390 LPRINT "ORIGINAL DISTANCE FROM THE WATER TABLE TO THE HIGH PERMEABILITY LAYER ";HP;" FEET."
22400 '
22410 IF QS=0 GOTO 22480
22420 LPRINT "OUTFLOW FROM STRUCTURE TO A UNDERLYING WATER TABLE";QS;" FT3/DAY/FT2.
22430 LPRINT "PERMEABILITY IN FT/DAY ";KS
22440 LPRINT "WIDTH OF DRAINAGE BLANKET IN FEET ";WS
22450 LPRINT "VERTICAL DISTANCE FROM DRAIN TO IMPERVIOUS LAYER IN FEET ";DS
22460 LPRINT "VERTICAL DISTANCE FROM ORIGINAL WATER TABLE TO IMPERVIOUS LAYER IN FEET ";HS
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22470 LPRINT "SLOPE OF THE IMPERVIOUS LAYER IN FEET RISE/FOOT RUN ";SS
22480 '
22490 IF QA=0 GOTO 22540
22500 LPRINT "ARTESIAN INFLOW  ";QA:' FT3/DAY/FT2"
22510 LPRINT "PERMEABILITY OF SUBGRADE SOIL IN FEET/DAY ";KA
22520 LPRINT "EXCESS ARTESIAN HEAD IN FEET ";DH
22530 LPRINT "THICKNESS OF SUBGRADE SOIL BETWEEN ARTESIAN AQUIFER AND DRAINAGE LAYER ";HA
22540 '
22550 IF QG=0 GOTO 22610
22560 LPRINT "FLOW INTO CUT FROM GRAVITY IS ";QG;" FT3/DAY/FT2"
22570 LPRINT "PERMEABILITY IN FT/DAY ";KG
22580 LPRINT "WIDTH OF DRAINAGE BLANKET IN FEET ";WG
22590 LPRINT "VERTICAL DISTANCE FROM DRAIN TO IMPERVIOUS LAYER IN FEET ";HG
22600 LPRINT "VERTICAL DISTANCE FROM ORIGINAL WATER TABLE TO IMPERVIOUS LAYER IN FEET ";HB
22605 LPRINT "AN ADDITIONAL";Q2;"FT3/DAY/FT WILL FLOW DIRECTLY INTO THE SIDE OF THE DRAIN.":LPRINT
22610 '
22620 IF QS=0 GOTO 22810
22630 LPRINT "OUTFLOW TO UNDERLYING WATER TABLE IS ";QS;" FT3/DAY/FT2."
22640 LPRINT "WIDTH OF PAVEMENT STRUCTURE IN FEET ";WS
22650 LPRINT "DEPTH TO THE IMPERVIOUS LAYER IN FEET ";DS
22660 LPRINT "ORINGINAL THICKNESS OF THE WATERTABLE OVER THE IMPERVIOUS LAYER IN FEET ";HS
22670 LPRINT "THE SLOPE OF THE IMPERVIOUS LAYER (FEET RISE/FOOT RUN) ";SS
22680 LPRINT "PERMEABILITY OF THE SOIL IN FEET/DAY ";KS
22690 LPRINT:PRINT
22810 'LONGITUDINAL INTERCEPTOR DRAINS
22820 IF QD=0 GOTO 22900
22822 LPRINT
22825 LPRINT "FLOW INTO LONGITUDINAL INTERCEPTOR DRAIN IS ";QD;" FT3/DAY/FT."
22827 LPRINT "THIS FLOW IS NOT INCLUDED IN THE NET FLOW IN STRUCTURE."
22830 LPRINT "PERMEABILITY OF SOIL IN FEET/DAY ";KD
22840 LPRINT "VERTICAL DISTANCE FROM ORIGINAL WATER TABLE TO IMPERVIOUS LAYER IN FEET ";HD1
22850 LPRINT "VERTICAL DISTANCE FROM BASE OF DRAIN TO IMPERVIOUS LAYER IN FEET ";HD
22860 IF BD=0 GOTO 22890
22870 LPRINT "WIDTH OF PAVEMENT STRUCTURE IN FEET ";WD
22875 LPRINT "WIDTH OF DRAIN IN FEET ";BD1
22880 LPRINT "MAX. HEIGHT OF WATER BETWEEN DRAINS IS ";HD2;" FEET.":GOTO 22900
22890 LPRINT "SLOPE OF ORIGINAL WATER TABLE ";SD
22900 GOTO 20950
22920 '
22930 '
22940 '
40000 ' TABLES OF TYPICAL VALUES OF SOIL PERMEABILITY
40005 CLS
40010 ' BASED ON TABLES 1,2 AND 3 OF THE HIGHWAY SUBDRAINAGE DESIGN MANUAL
40020 PRINT "PERMEABILITIES OF SOILS VARY WIDELY EVEN WITHIN A GIVEN SOIL TYPE. THE PERMEABI-LITY CAN BE MEASURED BOTH IN T
40025 PRINT "AN IMPORTANT DESIGN VARIABLE.  PERMEABILITY WILL TYPICALLY BE ANISOTROPIC AND"
40030 PRINT "HIGHLY INFLUENCED BY DISCONTINUITIES IN THE MEDIUM.  THE SUITABLE PERMEABILITY  FOR DESIGN PURPOSES SHOULD BE
40040 PRINT "CAN NOT BE EVEN ROUGHLY PREDICTED FROM THE AASHTO DESIGNATIONS DUE TO THE LARGE VARIABILITY IN THE ALLOWABLE Q
40050 PRINT "SOIL CLASSIFICATION SYSTEM BE USED TO FIND RANGE OF PERMEABILITY APPLICABLE TO  THE SOIL IN QUESTION."
40080 PRINT:PRINT "THIS SECTION WILL PROVIDE GENERAL GUIDENCE IN FINDING THE SUITABLE RANGE OF PER-MEABILITY FOR A SOIL."
40090 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
40092 '
40094 '
40100 ' TABLE 1
40105 CLS
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40110 PRINT "    TABLE 1.  TYPICAL VALUES OF SOIL PERMEABILITY"
40120 PRINT "SOIL DESCRIPTION      COEFFICIENT OF PERMEABILITY    DISCRIPTIVE"
40130 PRINT "                            K (FEET/DAY)                      TERM"
40140 PRINT
40150 PRINT "MEDIUM AND COARSE           >30                              HIGH"
40160 PRINT "    GRAVEL":PRINT
40170 PRINT "FINE GRAVEL; COARSE,      30-3                               MEDIUM"
40180 PRINT "MEDIUM AND FINE":PRINT "SAND; DUNE SAND.":PRINT
40190 PRINT "VERY FINE SAND; SILTY      3-0.03                            LOW"
40200 PRINT "SAND; LOOSE SILT;":PRINT "LOESS; ROCK FLOUR.":PRINT
40210 PRINT "DENSE SILT; DENSE       0.03-0.0003                      VERY LOW"
40220 PRINT "LOESS; CLAYEY SILT;":PRINT "SILTY CLAY.":PRINT
40230 PRINT "HOMOGENEOUS CLAYS          <0.0003                       IMPERVIOUS"
40500 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
40600 '
40610 '
41000 ' TABLE 2
41010 CLS
41020 PRINT "  APPROXIMATE CORRELATION BETWEEN PERMEABILITY AND"
41030 PRINT "          UNIFIED SOIL CLASSIFICATION SYSTEM":PRINT
41040 PRINT "UNIFIED SOIL CLASSIFICATION   COEFFICIENT OF PERMEABILITY K (FEET/DAY)
41050 PRINT:PRINT "          GW                                  2.7 - 274"
41060 PRINT "           GP                              13.7 - 27400"
41070 PRINT "           GM                           0.00027 - 27"
41080 PRINT "           GC                          0.000027 - 0.027":PRINT
41090 PRINT "           SW                               1.4 - 137"
41100 PRINT "           SP                              0.14 - 1.4"
41110 PRINT "           SM                            .00027 - 1.4"
41120 PRINT "           SC                          0.000027 - 0.14":PRINT
41130 PRINT "           ML                          0.000027 - 0.0027"
41140 PRINT "           CL                          0.000027 - 0.0027"
41150 PRINT "           OL                          0.000027 - 0.027"
41160 PRINT "           MH                         0.0000027 - 0.00027"
41170 PRINT "           CH                        0.00000027 - 0.000027"
41180 PRINT
41200 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
42000 '
42010 '
44000 ' ESTIMATING COEFFICIENT OF PERMEABILITY OF GRANULAR DRAINAGE MATERIALS
44010 ' BASED ON FIGURE 28
44020 CLS
44030 PRINT "THE FOLLOWING SECTION WILL HELP YOU ESTIMATE THE PERMEABILITY OF A"
44040 PRINT "DRAINAGE OR FILTER MATERIAL.  IT IS BASED ON FIGURE 28 OF THE MANUAL."
44100 INPUT "DRY UNIT WEIGHT OF MATERIAL IN (Lbs/FT3)";G
44110 INPUT "THE PERCENT OF THE MATERIAL WHICH PASSES A #200 SIEVE";P
44120 INPUT "THE EFFECTIVE GRAIN SIZE, D10, OF THE MATERIAL (mm)";D
44130 INPUT "THE SPECIFIC GRAVITY OF THE MATERIAL (DEFAULT 2.70)";S
44140 IF S>0 THEN 44200
44150 S=2.7
44200 ' POROSITY
44210 N=(1-(G/(62.4*S)))
44300 ' PERMEABILITY
44310 K=(621400.1*(D^1.478)*(N^6.654))/(P^.597)
44350 PRINT
44360 PRINT "BASED ON THE INFORMATION PROVIDED THE PERMEABILITY IS APPROXIMATELY";K;" FT/DAY"
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44400 PRINT
44500 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
48000 CLS:CLS
49000 RETURN
49100 '
49110 '
49120 '
50000 ' ILLUSTRATIONS FOR PROGRAM
50005 '
50010 '
51000 ' ILLUSTRATION FOR OUTFLOW TO UNDERLYING WATER TABLE
51010 SCREEN 2:CLS:KEY OFF
51020 PRINT:PRINT"        OUTFLOW  TO  A  WATER  TABLE  AT  DEPTH"
51030 PRINT:PRINT:PRINT:PRINT
51040 PRINT"                            ORIGINAL GROUND"
51050 PRINT:PRINT:PRINT:PRINT"                                       I----W---I":PRINT
51060 PRINT"     ORIGINAL WATER TABLE"
51070 PRINT:PRINT"             H                  Dr"
51080 PRINT:PRINT:PRINT:PRINT:PRINT "        IMPERVIOUS LAYER SLOPE S"
51200 '
51300 PSET (100,50)
51310 DRAW "M+500,+50;"
51320 DRAW "BM-400,-40;M+70,+30;R+70;"
51330 DRAW "M+40,-10;"
51340 DRAW "BM-280,+50;M+500,+50;"
51350 PSET (270,90)
51360 DRAW "D+55"
51370 PSET(+100,+85)
51380 DRAW "M+100,+10;M+70,-05;"
51390 PSET (+105,+87)
51400 DRAW "D42"
51410 PSET (270,89)
51420 DRAW "R+70;M+10,+9;M+20,+9;M+40,+9;M+80,+9;M+120,+12"
51430 DRAW "BM-20,+45"
51440 FOR I=1 TO 50
51450 DRAW "M+7,-1;BM-7,+1"
51460 DRAW "BM-10,-1"
51470 NEXT I
51500 PRINT
51600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
51700 SCREEN 0:CLS
51900 RETURN
51910 '
51920 '
52000 ' ILLUSTRATION FOR FLOW INTO A CUT DUE TO GRAVITY
52010 SCREEN 2:CLS:KEY OFF
52020 PRINT:PRINT "        FLOW  INTO  A  CUT  DUE  TO  GRAVITY"
52030 PRINT:PRINT
52040 PRINT"                          Li":PRINT:PRINT
52050 PRINT:PRINT"             ^                          0.5W"
52060 PRINT"                          Q1"
52070 PRINT"              H -------------------------"
52080 PRINT"                 ^"
52090 PRINT"                 Ho        K        Q2"
52100 PRINT:PRINT"             v     v"
```

```
52110 PRINT:PRINT "              IMPERVIOUS  LAYER"
52120 PRINT:PRINT
52130 '
52300 PSET (100,50)
52310 DRAW "R150;M+150,30;R100;"
52320 DRAW "BL100;M-75,-9;M-75,-6;M-75,-3;M-75,0;"
52330 DRAW "BD60;R400;BD20;U40;BU10;U20;BU10;U50;"
52340 DRAW "BL100;BD25;D50;R2;U2;R98;U2;"
52350 DRAW "BL353;BU20;D55;"
52360 DRAW "BR48;U30;"
52370 PAINT (405,81),1
52380 PSET (400,68)
52390 DRAW "R30;BR40;R30;"
52400 DRAW "BL310;BU10;U30;BD10;R10;BR50;R150;"
52600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
52700 GOSUB 55000
52800 SCREEN 0:CLS
52900 RETURN
52910 '
52920 '
53000 ' ILLUSTRATION FOR INFLOW FROM AN ARTESIAN AQUIFER
53010 SCREEN 2:CLS:KEY OFF
53020 PRINT:PRINT "                             INFLOW FROM AN ARTESIAN AQUIFER"
53030 PRINT:PRINT
53040 PRINT"                             PIEZOMETRIC  LEVEL"
53050 PRINT:PRINT
53060 PRINT"                                   ^"
53070 PRINT:PRINT
53080 PRINT"                                  Ho              K"
53090 PRINT
53100 PRINT"                                   v"
53110 PRINT
53120 PRINT"                              ARTESIAN  AQUIFER"
53130 '
53300 PSET (100,35)
53310 DRAW "R120;BR200;R120;BL440"
53320 DRAW "BU20;R100;M+50,+40;R200;M+50,-40;R100"
53330 DRAW "BM-301,+40;D48;BL200;R500"
53340 PRINT:PRINT
53400 PRINT:PRINT
53600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
53700 SCREEN 0:CLS
53900 RETURN
53910 '
53920 '
54000 ' ILLUSTRATION FOR SYMMETRICAL EDGE DRAINS
54010 SCREEN 2:CLS:KEY OFF
54020 PRINT "        SYMMETRICAL  INTERCEPTOR  DRAINS  IN  A  CUT":PRINT
54030 PRINT"                    ^":PRINT
54040 PRINT"                             PIEZOMETRIC  LEVEL"
54050 PRINT:PRINT "FINAL PHREATIC":PRINT"    SURFACE":PRINT
54060 PRINT"                    H       ^"
54070 PRINT"                            Ho              K"
54080 PRINT
54090 PRINT"                    v       v"
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54100 PRINT
54110 PRINT"                              IMPERVIOUS LAYER"
54120 PRINT:PRINT
54310 PSET (100,35)
54320 DRAW "R120;BR200;R120;BL440"
54330 DRAW "BU20;R100;M+50,+40;R200;M+50,-40;R100"
54340 DRAW "BM-350,+40;D15;R5;U12;R190;D12;R5;U15"
54350 PAINT (301,57),1
54360 PSET (250,70)
54370 DRAW "D33;BL62;U87;BM+70,+87;BL175;R500"
54380 PSET (100,45)
54390 DRAW "M+37,+3;M+37,+4;M+35,+7;M+35,10"
54400 DRAW "M+10,+3;M+20,-3;M+50,-3;M+50,0;M+50,+3;M+20,+3;M+10,-3"
54410 DRAW "M+35,-10;M+35,-7;M+37,-4;M+37,-3"
54600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
54700 SCREEN 0:CLS
54900 RETURN
54910 '
54920 '
55000 ' CONFIGURATION OF ROADWAY
55010 SCREEN 2:CLS:KEY OFF
55020 PRINT "NOTE THE DEFINITION OF THE WIDTH OF THE PAVEMENT"
55030 PRINT
55040 PRINT "                                            WIDTH"
55050 PRINT:PRINT:PRINT:PRINT:PRINT:PRINT
55060 PRINT "                                            WIDTH"
55070 PRINT:PRINT:PRINT:PRINT:PRINT:PRINT:PRINT
55090 '
55100 PSET (100,10)
55110 DRAW "M+100,+10;BM+300,+30;M+100,+10"
55120 PSET (200,20)
55130 DRAW "M+50,+20;M+250,+10;D15;L5;U10;M-245,-10;U5"
55140 PAINT (251,41),1
55150 PSET (250,40)
55160 DRAW "BU5;U10;D5;R250;U5;D15"
55500 PSET (100,100)
55510 DRAW "M+100,+10;M+150,-10;M+150,+10;M+100,-10"
55520 DRAW "BM-100,+10;D15;L5;U10;M-145,-9;M-145,+9;D10;L5;U15"
55530 PAINT (201,111),1
55540 PSET (350,100)
55550 DRAW "BU5;U15;D5;R150;U5;D20"
55600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
55700 SCREEN 0:CLS
55900 RETURN
55910 '
55920 '
56000 'ILLUSTRATION FOR FLOW TO A PERMEABLE LAYER AT DEPTH
56010 SCREEN 2:CLS:KEY OFF
56100 PRINT:PRINT"   OUTFLOW TO A PERMEABLE LAYER AT DEPTH"
56110 PRINT:PRINT
56120 PRINT "                        PAVEMENT SURFACE"
56130 PRINT"                             ^"
56140 PRINT:PRINT:PRINT:PRINT "       ^                                          WATER TABLE"
56150 PRINT:PRINT "      Ho                    H          K"
56160 PRINT"      v                     v":PRINT:PRINT:PRINT
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56170 PRINT"       HGIH PERMEABILITY LAYER "
56180 PRINT "      K HIGH PERMEABILITY LAYER MUST BE TEN TIMES K SUBGRADE"
56190 PRINT:PRINT
56300 PSET (50,60)
56310 DRAW "R100;BR300;R100;L100;M-50,-20;L200;M-50,+20"
56320 DRAW "BM50,70,R40;BR460;L40;M-40,-3;M-30,-5;M-20,-5;M-10,-6;M-10,-10"
56330 DRAW "BL200;M-10,+10;M-10,+6;M-20,+5;M-30,+5;M-40,+3"
56340 DRAW "BM50,103;R500"
56350 FOR I=1 TO 5
56360 FOR J=1 TO 25
56370 DRAW "L10;BL10"
56380 NEXT J
56390 DRAW "BD4;BR500"
56400 NEXT I
56410 DRAW "BM59,70;D30;BR200;U60"
56600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
56800 SCREEN 0:CLS
56900 RETURN
56910 '
56920 '
57000 'OUTFLOW THROUGH EMBANKMENT AND FOUNDATION SOIL
57010 SCREEN 2:CLS:KEY OFF
57100 PRINT:PRINT"    OUTFLOW THROUGH EMBANKMENT AND FOUNDATION SOIL"
57110 PRINT "                                        .5W        Lf"
57120 PRINT:PRINT
57130 PRINT "       ^  ":PRINT "          Hf                    ^"
57140 PRINT"       v ":PRINT "                                       WATER TABLE AT GROUND SURFACE"
57150 PRINT:PRINT:PRINT "                                 Dr          K"
57160 PRINT"                            v":PRINT
57170 PRINT"       IMPERVIOUS LAYER"
57190 PRINT:PRINT "Hf = HEIGHT OF EMBANKMENT        Df = DEPTH TO IMPERVIOUS LAYER"
57200 PRINT "0.5W = WIDTH OF PAVEMENT FOR SYMMETRICAL CONFIGURATION"
57210 PRINT "Lf = DISTANCE FROM EDGE OF PAVEMENT TO TOE OF EMBANKMENT"
57220 '
57300 PSET (50,60)
57310 DRAW "R100;BR300;R100;L100;M-50,-20;L200;M-50,+20"
57320 DRAW "M+50,-5;M+30,-5;M+20,-10;D10;R3;U6;R100;D6;R3;U10"
57330 DRAW "M+20,+10;M+30,+5;M+50,+5"
57340 DRAW "BM50,103;R500"
57360 FOR I=1 TO 50
57370 DRAW "M-10,+3;BM+10,-3;L10"
57380 NEXT I
57410 DRAW "BM59,60;U20;BL10;R140;BR70;BD5;D55"
57420 DRAW "BM300,40;BU5;U15;D5;R53;U5;D15"
57430 DRAW "U10;R100;U5;D35"
57500 PAINT (301,41),1
57600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1):PRINT
57800 SCREEN 0:CLS
57900 RETURN
57910 '
57920 '
58900 RETURN
58910 '
58920 '
59000 'EDGE DRAIN
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59010 SCREEN 2:CLS:KEY OFF
59100 PRINT "EDGE DRAIN DESIGN INTRODUCTION"
59110 PRINT:PRINT
59120 PRINT "          OUTLET SPACING                    CAR"
59130 PRINT:PRINT:PRINT
59140 PRINT "       PAVEMENT "
59150 PRINT "       SURFACE                     SLOPE          PAVEMENT SURFACE"
59160 PRINT:PRINT"                EDGE DRAIN"
59170 PRINT "      OUTLET "
59172 PRINT "                                                     DRAINAGE BLANKET"
59174 PRINT "                                          EDGE DRAIN"
59180 PRINT "                                                      CROSS SECTION"
59190 '
59310 PSET (50,80)
59350 DRAW "M+500,-50;D06;M-500,+50;U06;D3;M+500,-50;M-500,+50":PAINT (58,83)
59355 PSET (50,80)
59360 DRAW "BU20;U30;BD5;R200;BU5;D20"
59370 DRAW "BM+100,-5;M+101,-10;M-3,-10;M-20,+2;M-15,-9;M-25,+2;M-15,+12;M-25,+2;M+3,+10"
59380 CIRCLE (375,44),8
59390 CIRCLE (425,39),8
59400 CIRCLE (50,87),5:CIRCLE (250,67),5
59500 PSET (350,80)
59510 DRAW "M+50,+5;M+75,-05;M+75,+5;M+50,-5"
59520 DRAW "BM-50,+5;D7;L2;U5;M-73,-4;M-73,+4;D5;L2;U7"
59530 PAINT (401,86),1
59540 PSET (350,100): DRAW "M+45,-10;BR080;U2;D5"
59600 PRINT "STRIKE ANY KEY TO CONTINUE.";:A$=INPUT$(1)
59700 SCREEN 0:CLS
59900 RETURN
59990 '
59992 '
59994 '
60000 ' EDGE DRAIN DESIGN
60050 GOSUB 59000
60100 ' DRAIN MATERIAL SELECTION
60105 CLS:PRINT
60110 PRINT "SELECT THE DRAIN MATERIAL TO BE USED "
60120 PRINT " 0 PLASTIC PIPE"
60130 PRINT " 1 HYDRAWAY"
60140 PRINT " 2 AKWADRAIN"
60150 PRINT " 3 HITECK 20"
60160 PRINT " 4 HITECK 40"
60170 PRINT " 5 NONE OF THE ABOVE"
60180 PRINT
60200 PRINT "ENTER THE NUMBER OF YOUR SELECTION ";:A$=INPUT$(1):PRINT
60205 PRINT
60210 INPUT "WHAT IS THE SLOPE OF THE DRAIN LONGITUDINALLY";SE
60215 PRINT
60220 PRINT "IS THIS DESIGN TO SELECT THE SIZE OF THE DRAIN OR OUTLET SPACING (D/O)";:T$=INPUT$(1):PRINT T$
60230 IF T$="O" OR T$="o" GOTO 60260
60235 PRINT
60240 INPUT "WHAT IS THE OUTLET SPACING IN FEET";OS
60245 PRINT
60250 GOTO 60280
60260 PRINT
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60270 INPUT "WHAT IS THE DRAIN SIZE ( RADIUS FOR PIPE OR HEIGHT FOR GEOCOMPOSITES ) IN INCHES";DS
60275 PRINT
60280 INPUT "WHAT IS THE DESIGN INFLOW IN FT3/DAY/LINEAR FOOT OF DRAIN";QI
60285 PRINT
60290 QI=QI/86400!
60310 IF A$="0" THEN GOTO 60500
60320 IF A$="1" THEN C=1333
60330 IF A$="2" THEN C=528
60340 IF A$="3" THEN C=584
60350 IF A$="4" THEN C=2030
60360 IF A$="5" THEN GOTO 60380
60365 PRINT "IF THE DRAIN IS A DOUBLE SIDED DRAIN WILL BOTH SIDES BE EMPLOYED (Y/N)";A$=INPUT$(1)
60367 IF A$="Y" OR A$="y" THEN C=C/2
60368 PRINT
60370 GOTO 61000
60380 INPUT "INPUT THE MATERIAL CONSTANT TO BE USED";C
60390 GOTO 61000
60392 '
60394 '
60500 ' PLASTIC PIPE
60510 PRINT "IS THE PIPE SMOOTH OR CORRUGATED (S/C)?";:B$=INPUT$(1):PRINT
60520 IF B$="C" OR B$="c" THEN N=.024 ELSE N=.013
60525 PRINT
60527 '
60550 'FIND DIAMETER OF PIPE
60560 IF T$="O" OR T$="o" THEN GOTO 60600
60570 R=((N*QI*OS)/(1.486*(SE^.5)))^(3/8)
60575 R=INT(R*100)/100
60580 PRINT "THE REQUIRED RADIUS IS ";R*12;" INCHES."
60590 GOTO 65000
60595 '
60600 'FIND OUTLET SPACING
60605 R=DS/12
60610 Q=(.9362/N)*R^2.6667*3.1415*SE^.5
60620 OS=INT(Q/QI)
60630 PRINT "THE REQUIRED OUTLET SPACING IS ";OS;" FEET.":GOTO 65000
60632 '
60634 '
61000 'GEOCOMPOSITE DRAIN DESIGN
61010 QI=QI*86400!
61050 IF T$="O" OR T$="o" THEN GOTO 61200
61060 '
61100 'SIZING DRAIN
61110 FOR H=0 TO 48 STEP 2
61120 IF QI*OS<C*H*(SE+H/(12*OS))^.5 THEN GOTO 61140
61130 NEXT H
61135 PRINT "THE REQUIRED SECTION WOULD BE PROHIBITIVELY DEEP.  PLEASE MODIFY YOUR INPUT.":GOTO 60000
61140 PRINT "THE REQUIRED HEIGHT OF DRAIN IS ";H;" INCHES."
61145 PRINT "WITH A GRADIENT OF ";H/(12*OS)+SE
61150 GOTO 65000
61152 '
61200 'OUTLET SPACING
61210 FOR OS=10 TO 2000 STEP 10
61220 IF QI*OS>C*DS*(SE+DS/(12*OS))^.5 THEN 61240
61230 NEXT OS
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61240 PRINT "THE REQUIRED OUTLET SPACING IS ";OS;"FEET."
61245 PRINT "WITH A GRADIENT OF ";DS/(12*OS)+SE
61250 GOTO 65000
65000 RETURN
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